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(Unclassified Title)

UNSOLICITED PROPOSAL FOR IMAGE ANALYSIS

Proposal No. TO-B 88-66

23 December 1966

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CHAPTER 1

INTRODUCTION

OBJECTIVES

During the past nine months a completely new approach in viewing the problem of image analysis has begun. And the results of this effort have already uncovered and specified significant problem areas that the community were generally unaware of. For instance, the new understanding of the effects of coherence on imaging systems in general has led to the necessity for a complete reappraisal of the interpretation of the data obtained using these systems. Criteria can now be stated for the range of validity of linear systems analysis procedures as applied to a number of system types. The next step, of course, is to make positive use of these studies to (1) evaluate current procedures, techniques, and systems, and (2) to suggest and incorporate new procedures and redesign systems to improve the reliability of data extraction.

While it is our primary purpose to develop a more fundamentally sound image theory and apply it to the exploitation of high resolution transilluminated photography, it must be remembered that there are pressing problems which need to be solved now. Our work to date has established a range of validity of current theory. More precisely, we have not found the upper bound on this theory, but we are confident that current techniques are applicable up to at least 50 ℓ/mm. Therefore, in the early stages of the proposed program in which color photography is studied and in which model emulsions are used, we shall make extensive use of such concepts as effective exposure and film MTF even though our basic study shows that these concepts are not extendable to higher line frequencies. In this way pressing problems can be treated even as the theory is being developed.

The main purpose of this program is to improve the Center's capability of image exploitation by providing a better understanding of image formation and transformations and then applying this better understanding to the development of improved exploitation procedures and instrumentation. Toward this end, two things must be considered:

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1. The detailed relationship between our proposed program and the various missions of NPIC

2. The detailed relationship between the various aspects of the image formation and exploitation process and our program.

The first of these relationships is discussed at length in our Task 1-b report on the current phase of this program. For security reasons that report cannot be reproduced here but is included by reference and should be read by those interested in seeing the relationship between this program and the Center's mission. That report also discusses at length some of the classified instrumentation and development problems to be considered in this program. In discussing the second relationship, it is convenient to divide image exploitation in several broad categories and to consider each separately:

1. Collection
   - a. camera systems
   - b. film systems
2. Processing
   - a. preparation of the original negative emulsions (ON)
   - b. preparation of the duplicate positive emulsion (Dupe)
3. Viewing
   - a. light tables and auxiliary optics
   - b. projection
4. Mensuration
   - a. machine
   - b. visual
5. Diagnostics
   - a. camera system malfunctions
   - b. photographic problems
6. Color
   - a. conventional
   - b. TOC and spectral zonal
7. ~~Support of other NPIC programs~~

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COLLECTION

For the most part collection problems lie outside the domain of NPIC's interest and, therefore, the collection problem centers only peripherally on our program. Though we shall not be concerned with the design of IMC systems or other camera subsystems, it is imperative that the theory we develop be broad enough to encompass such considerations as they affect image quality and exploitation. Thus, for example, a part of the [redacted] study is a consideration of the thermal 25X1
sensitivity of certain lens design configuration of interest in the collection system. This point is discussed in Task 1-b report.

The film type for the collection system is rather firmly established. Once again, however, as our film studies progress each new concept or technique developed will be used to re-examine the question of whether the film type can be further optimized.

PROCESSING

The method of film processing and the selection of processing chemicals can have a significant effect on the usefulness and interpretability of the finished product; furthermore, the processing chemistry and technique can have a direct influence on the applicability of a given theory of image formation as applied to the photographic process. Accordingly, a major portion of our four year program is devoted to this topic.

Broadly, our plan is as follows. By preparing model emulsions of gradually increasing sophistication, in which each of the photographic parameters is systematically varied, we hope to develop a basic theoretical relationship between the emulsion parameters (such as gelatin type, grain size distribution, morphology, and sensitization) and the structure of the final photographic image. This fundamental study will be conducted by [redacted] using their 25X1
emulsion and developer formulation facility and the precision electron microscope techniques. The model emulsions and developers prepared by [redacted] will be 25X1
supplied to the subcontractors for use in the phenomenological studies being pursued there.

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These studies and the theory developed will be applied both to the processing of the ON and to the understanding of the Dupe problem; that is, the problem of grain on grain duplication. It is hoped that during the third and fourth years of the program these studies will lead to improvements in the design of processing formulations and equipment as well as the development of optimized films.

In addition to this fundamental or mechanistic approach to the formation of an image theory for the photographic process, two more prognostic or phenomenological approaches to developing such a theory are being pursued by [redacted] 25X1
[redacted] The two approaches are analogous to a thermodynamic 25X1
description of gas pressures, whereas the fundamental study is similar to a molecular description of the same phenomena. At [redacted] the point of 25X1
view adopted is that the relationship between exposing light distribution and resulting transmission is best described as a nonlinear filtering and that the techniques of nonlinear stochastic analysis may be used to develop useful relationships even if the mechanisms are not fundamentally understood. An alternate phenomenological approach being pursued at [redacted] is to assume that fundamentally 25X1
the photographic image is a collection of developed grains. Therefore, by studying the statistics of the photographic grain one should be able to discover the statistical invariants which form the basis upon which to build an image theory. (For example, resolution should be predictable from a study of the grain statistics.)

VIEWING

Viewing the final image is without question the most important part of the problem from NPIC's point-of-view and will therefore be given major emphasis. As pointed out in our Task 1-b report, the most characteristic description of the Center's viewing problem is "exploitation of high resolution transilluminated first positive transparencies." As suggested in our original proposal and substantiated in our studies thus far, this situation is fundamentally a different image formation problem than that of the taking system. The coherence of the illumination is a problem of the viewing system but not of the taking system.

At [redacted] we are studying, in depth, the nonlinear imaging properties of 25X1
systems employing partially coherent light. The theory of partial coherence is being extended and applied to the description of transilluminated imaging systems

from tube magnifiers to microdensitometers. It is hoped that as such systems are better understood and the theory is made more complete the design of these exploitation instruments can incorporate optimized light sources and condensing systems so that the coherence problems are minimized or eliminated. This part of the program is progressing rapidly, and it is felt that by next year this theory will result in significant changes in the design of viewing instruments. Further, the study of the coherence in the microdensitometer illumination chain should be completed within the scope of the first year's programs so that its results can influence microdensitometer design in the following year.

Realizing that coherence effects can never be eliminated at extremely high line frequencies, [redacted] part of the program includes a study of the influence of partial coherence of the design of optimum lens systems for viewing instruments. Since a significant portion of NPIC's procedure involves the use of stereo imagery, the coherence effects in this viewing situation should also be examined in depth to ascertain whether the illumination considerations are the same as for two-dimensional imagery. Another aspect of the viewing problem is image restoration and other image processing techniques such as the IDT analysis. We feel that our understanding of these problems has already progressed to the point that practical restoration problems can be undertaken. 25X1

MENSURATION

In our briefings at NPIC we were told that a large percentage of the photo-intelligence (perhaps 90%) was obtained by mensuration. On the basis of that briefing, we initiated a special task involving [redacted] and the personnel of AFSPPF at Westover to study the factors affecting mensuration accuracy in both the ON and Dupe material. This study involves laboratory generated material and mission material. In particular, machine mensuration (using a microdensitometer) is being compared with visually read mensuration (using cross hairs and a microscope) in a study involving only targets for which object truth is known. This study involves collecting a large number of data points over the next six months and is already showing significant results. We expect to be able to make specific recommendations by the end of the current phase of the program and to implement them in later phases. 25X1

DIAGNOSTICS

Diagnostics in image analysis describes the process of isolating and identifying system difficulties by examining the output of an imaging system. This problem area is not specifically within the mission of NPIC and consequently plays a minor role in our overall program. However, the theory being developed is applicable to this problem area and, therefore, we are including such studies peripherally.

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SUPPORT OF OTHER NPIC PROGRAMS

The Center is presently supporting several major programs including non-conventional imagery, human factors, and automatic target recognition. All of these programs require an adequate image theory and a self-consistent system of image analysis. Through constant liaison we are supplying what support is possible in these areas, and we expect this part of our program to become more important as time goes on. At present we are, of course, directly involved in the Automatic Target Recognition program and are making arrangements to provide consulting, model emulsions, targets, and measurement techniques to the Human Factors Program.

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CHAPTER 2

NINE MONTH PROGRAM AND CONTINUATION

SECTION A: CHEMISTRY AND OPTICS

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CHEMISTRY

Four Year Goal

The four year goal of the chemistry phase of the Image Evaluation program is to determine by experiment the relationship between the parameters of the photographic emulsion itself, the procedures used to process it, and the image quality of the resultant processed emulsion so that ultimately the emulsion types and processing procedures used by the Sponsor can be altered to give him improved results in his specific mission, new materials can be submitted to the Sponsor, and the Sponsor can better understand his image quality problems in terms of the emulsion and processing parameters.

By emulsion parameters we mean those such as:

1. Grain size distribution (GSD)
2. Grain morphology (type of crystal)
3. Emulsion coverage (coating weight)
4. Emulsion thickness
5. Type of sensitization (including spectral sensitization).

By processing procedures we mean development and fixation as they affect:

1. Developed characteristics as a function of line frequency
2. Image quality as a function of line frequency and developed density
3. The relationship between the grain size distribution of the receptor emulsion, and the opaque area and structure of the developed emulsion grains.

By image quality we presently mean the behavior of the emulsion with respect to MTF, AIM, granularity, and 3-bar resolution criteria; the ability of an original negative emulsion (ON) to be duplicated; the ability of a duplicate to be observed; and other criteria to be developed on other phases of the program.

By the term emulsion we mean two specific emulsion types: the original negative emulsion (ON) type, which is to be exposed by a lensing system and used as a master for duplicating; and the duplicate positive emulsion (Dupe), which is to be exposed by contact from the ON and used for image interpretation as a positive transparency over a specific range of image magnification.

Our experimental procedures will be those of emulsion fabrication and coating, study of GSD and developed image structure by optical and electron microscopy, and evaluation of image quality by up-to-date experimental methods.

We believe that the results of our four-year program will appear in three forms:

1. An explanation of image quality behavior (of both the ON and Dupe) as a function of imagery source, of density, and of line frequency, in terms of emulsion and processing parameters, so that limits and expectations for system image quality can be established by the Sponsor.

2. Explicit functional relationships between the pertinent emulsion parameters and an appropriate image theory.

3. A number of specific suggestions in the form of new emulsions, new processing procedures, or new observational procedures that will improve the overall quality of performance of the Sponsor's missions, perhaps in specific ranges of density or line frequency, in the improvement of image quality assessment criteria, or in overall imagery performance.

Proposed Program

The four year Chemistry Image Evaluation program is presently concluding Phase 1 of 9 months which will terminate 1 April 1967. We shall first briefly describe the attained and expected accomplishments of this program. The proposed Phase 2 continuation of this program, to extend from 1 April 1967 to 1 January 1968, will then be described. Finally, a general description of Phase 3, to extend from 1 January 1968 into 1971 and to accomplish the goals stated above, will be discussed.

Phase 1 (July 1966 - April 1967)

Accomplishments — One goal of the chemistry program is to obtain an understanding of the relationship between the original GSD of a controlled series of photographic emulsions and the developed GSD, as this change may pertain to image quality. The experimental methods used in achieving this goal are those of controlled emulsion preparation and coating, and the use of optical and electron microscopy. Other goals of Phase 1 are to obtain data on existing films of interest to the Sponsor and to establish image quality procedures to be used on existing and experimental emulsions.

Photographic emulsions of known crystallographic grain size and of narrow grain size distribution (uniformity of size), with known and controlled gelatins, have been, and are being, prepared by controlled preparation procedure. (The only variable in these first emulsions has been grain size.) Some of these emulsions have been submitted to [redacted] for granularity measurements as part of their theoretical program. All characteristic curves, GSD curves, and image quality parameters are being measured at [redacted] and the data supplied to [redacted]

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Model emulsions, prepared as described above, have been exposed and developed under controlled conditions to determine the relationship between unexposed and exposed GSD curves and the maximum average grain areas. (Later in the program they may be exposed to varying densities at various spatial frequencies, to edges, or to bar targets. The developed silver will in all cases be observed in the electron microscope, and we shall attempt to relate image structure with emulsion parameters. We shall study theories of image quality, based on granularity, using these controlled emulsions for experimental varification.)

Electron microscopy experimentation has been a major task. Presently, the microscope is operating and sample preparation is under study. For example, the undeveloped grains can be observed by direct or indirect replication, while the developed silver can be observed directly. The observation of film cross sections may be possible by using microtome methods with or without replication.

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Accomplishments of Phase 1 as of December 1966 comprise the following. We have prepared emulsions whose grain structure is octahedral (triangular and hexangular platelets) and cubic, and our choice of grain size has been established as cubic. We have obtained well-defined grain size distribution, using the double-jet precipitation method, and have established GSD curves for all emulsions prepared. A series of developers has been prepared that show small, large, and clumped developed grains, and a relationship has been established between developed and undeveloped grains for a monolayer emulsion of known GSD. We find that the ratio α of the GSD maximum for developed to undeveloped grains, $\sigma d/\sigma u = \alpha$, increases with developed density, indicating a loss of image quality at high density, independent of the scattering of the incoming light. The theory of emulsion coverage has been investigated in so far as this affects the preparation of the model emulsions.

In cooperation with [redacted] we are studying the prediction of the resolution limit of a film based on the measured granularity, using our model emulsions for the experiments. We have studied the possibility of calculating, via a computer program, the recording of an edge on photographic film, taking into account only the light scattering through the granular layer. 25X1

We have also obtained characteristic and image quality data on films 3404, 8430, and 5427, so that the parameters of these films can serve as a guide to our experimentations on model emulsions.

Expected Accomplishments by the End of Phase 1 — Our principal experimental goal for the end of Phase 1 is to develop our electron microscope and image evaluation methods to the point that we can observe and study model emulsions in the 3404 film class. This will allow us to extend our present observations on coarse grained emulsions into the range of fine grain emulsions where we expect little difficulty in establishing coating and thickness measurement techniques by the conclusion of the program. We expect also to have well established our series of controlled emulsions and processing procedures, which will allow us to pursue our logical plans for image evaluation studies.

Phase 2 (April 1967 - January 1968)

In Phase 2 we plan to continue in depth our studies of image quality on the ON and to initiate our studies on the image quality problems of duplication. We shall first describe some details of our proposed studies on model ON emulsions and will then go on to a description of proposed work on the duplication emulsion (Dupe).

ON Model Emulsion Studies — In Phase 2, our experimental methods will be those described on p. 2-2 ; emulsion and developer preparation, electron microscope observation, and image quality measurements will be based on edge trace MTF analysis, AIM curves, and granularity. The specific subjects to be studied will include:

1. Contribution to image quality of emulsion thickness at constant GSD and processing conditions
2. Contribution to image quality of coating weight (mg/cm^2) at constant emulsion thickness
3. Characteristics of the developed grain as a function of exposure and depth in the emulsion layer
4. Developed grain size as a function of the distribution of latent image centers
5. Contribution of development to the spread function
6. Other topics that may derive from the above work.

Item 1. Our coating facility will enable us to produce a series of emulsions in which the film thickness can be varied from a monolayer grain coverage up to about twenty grain layer thicknesses. Such a wide range should allow us to go through the thickness ranges found in commercial emulsions of interest to the Sponsor. Moreover, all other parameters — GSD, grain morphology, and if possible coating weight — will be kept constant.

The resulting films will be exposed at various levels and the MTF and AIM curves will be derived. Electron microscope pictures of microtomed sections should reveal the depth and distribution of the developed grain. The key problem we wish to study here is the degree of degradation of the image that may occur in the depth of the emulsion.

Item 2. A parallel series of experiments will be conducted where the emulsion coating weight is varied at constant emulsion thickness. This could be achieved by variation in the concentration of chrome alum, glyoxal, or mucochloric acid added just prior to coating. In a first series of experiments the mean intergrain distance can be held constant and large. This would eliminate much of the variation due to development adjacency effects. It also would preserve the form of the scattering component of the spread function. It would then allow the spread to be examined purely as a function of depth of the image since this varies with developed density. In a second series of emulsions the form of the spread function would be changed by the change in grain relationship. Development characteristics will also be affected, but these can be isolated in turn by variation of exposure for any given film sample.

Item 3. Preliminary studies in progress at this time (December 1966) on the relationship between developed grain morphology and the original GSD have revealed several interesting effects that bear on image quality. They have shown that the final silver developed GSD for any given original silver halide GSD is a function of the exposure; the more heavily exposed grains develop to a larger mean area than the more lightly exposed grains. These findings may be significant in the interpretation of resolution data at high line frequencies. It is hoped that such phenomena can be studied as a function of developer and emulsion composition in order to discover what parameters are significant for the optimization of resolution at higher density. It is possible, for example, that an understanding of the principles of the phenomenon may lead to emulsion formulations which will extend the resolution latitude of the system, i.e., that resolution be less exposure dependent.

These preliminary studies have been conducted using optical microscopy on large grained emulsions, and our results have been gathered from interpretation of grain-size distribution data. In Phase 2 we plan to examine grain systems in which the mean grain-size is sub-one μ^2; therefore, electron microscopy will be imperative. Such observations will be made at a relatively low magnification since it is the distribution of many grain sizes that will be of interest, rather than

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the structure of single grains. However, the observation of developed single grains under high magnification will be necessary in our study of the imagery produced by the silver filaments.

Item 4. A study of the relationship between the number of nucleation centers on a grain and the developed grain size has become manifest as a result of our studies on Phase 1. Item 4 may be worthy of separate support since it is a new subject that relates to both latent image theory and image quality. As just described, one of the discoveries made so far is that the developed grain size is a function of the exposure and is likely to be significant at high line frequencies. An obvious explanation of this phenomenon is to be found in the consideration of the latent image distribution as a function of exposure. It is well known that the process of chemical sensitization, to which all modern emulsions are subjected, is the creation of deep trapping centers at a limited number of localized sites on or throughout the silver halide microcrystal lattice. In the case of sulfur sensitization, which is the commonest method of sensitization, silver sulfide molecules are deposited on the surface of the crystals, and it is to such regions that the photoelectrons move and are ultimately trapped by silver ions to produce atomic silver. These centers are therefore the nucleation centers for development. It was shown at Turin* that there is a distribution of such centers over any given crystal, and that their electron trapping capability also has a distribution. Under conditions of longer time and lower intensity exposure, the deepest trap can accommodate all photoelectrons since they arrive in a stepwise fashion, with relatively longer intervals between each arrival when compared with the electron trapping time. The net result is that only one center per crystal is formed. Under conditions of shorter time and higher intensity exposure, the photocapture rate is comparable with the electron trapping rate, and so some electrons are relegated to shallower electron traps. The net result is that at higher exposures each grain possesses several development nucleation centers. It is believed that what we have observed in our preliminary studies is a manifestation of this variation in nucleation centers, the morphology and rate of development being a function of the number of nucleation centers.

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*H. E. Spencer and R. E. Atwell, Turin Symposium, 1963

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It is possible to change the number and distribution of sensitivity centers by control of sensitization conditions during emulsion preparation. We propose that, by studying these center distributions as a function of emulsion manufacture and developer response, less degradation of high line frequencies may be achieved by suppression of those characteristics tending to spread the developed area of the exposed grain. The construction of a mathematical model embracing the underlying reactions and concepts is in progress and appears to reflect the observed trends at least in a qualitative manner. If such a model were coupled with a series of controlled emulsion preparation experiments, the number and distribution of centers available for electron capture would then be revealed and would greatly assist optimization of this parameter.

Item 5. A proposed experiment on the contribution of infectious development to image degradation has arisen from our results of Phase 1 and may be worthy of additional support. Present image evaluation techniques for photographic systems are based on linear systems analysis, and as such by far the greatest deviant component, is the emulsion itself. The currently favored solution to this problem is the concept of effective exposure. This method "corrects" the actual exposure by reference to the characteristic curve of the emulsion. The technique assumes that the spread function — which has at least three components, (1) the purely physical part due to light scattering of the emulsion grains, (2) the chemical part due to proximity effects of developing grains, and (3) the chemical effect of changing grain sizes and shapes — is linear. While the first component is linear in exposure, the latter effect is almost certainly nonlinear. It is impossible by conventional techniques to examine the influence of the developing grain on an adjacent unexposed grain because of the uncertainty in exposure boundaries, i.e., when two adjacent grains are considered it is not possible to determine whether one has been exposed while the other has not.

The degree of infectious development, as it may affect image quality, can be determined by a proposed experiment involving radio-tracer techniques. Two emulsions of exactly the same type are made: one containing radio-silver, and one a control. The active emulsion is fully exposed in the liquid state and then the two emulsions are combined in a 1 to 1 ratio, and the mixture is coated without further exposure. Subsequent development of this coated emulsion should yield no radioactivity of the final fixed film if infectious development does not occur. If, however, the development products in the vicinity of a nonactive exposed grain affect an adjacent radioactive unexposed grain to the extent that it also becomes developed, then subsequent washing of this film will not remove the radioactive silver metal which has been created by the infectious development. Thus, a measure of the residual radioactivity of the final film is a direct measure of the infectious development.

This parameter can be studied as a function of developer type and silver coating weight and, thus, yield a series of relationships for different developers describing the sphere of influence of a developing grain. There are several possible ways of performing the needed measurements:

1. The small γ activity associated with the particular isotope proposed $\left(Ag^{110}\right)$ may fog the emulsion and thus simulate exposure. A similar effect may be seen by the β-ray electron emission of the isotope whose major energy is of the order of 87 keV. It is known that radio sulfur (S^{35}) with an energy of 16 keV does not affect the emulsion, but it may be possible that the higher energy of both the γ and β emissions of the silver is sufficient to fog the film. Providing this effect is not great, it can be accomodated by a previous experiment in which neither of the emulsions is exposed to light. The residual count in this case will be a measure of this anti-fogging and may be considered as background noise.

2. There may be some exchange of radio silver with nonactive silver from one grain to another. This difficulty can be accomodated by the same experiment as in item one. The criterion for the success of the experiment is that the total noise contribution arising from these two possible snags be a minor proportion of the total activity.

Item 6. Selective topics will be determined in the course of the conclusion of Phase 1 and the pursuance of Phase 2.

Duplication — The image quality studies performed on model negative emulsions have a direct carry-over to duplicate emulsion. Several differences, however, exist between the Dupe and the ON that bear on the image quality problem:

1. The Dupe is not dye sensitized, while the ON is panchromatic. This influences the choice of grain morphology of the Dupe.

2. The Dupe need not be of high speed (sensitized), while the ON must be as sensitive as possible. This influences the GSD.

3. The Dupe is exposed only by contact to a photographic silver image using quasi-monochromatic blue light, while the ON is exposed through a lens system to polychromatic (minus blue) light.

4. The Dupe is generally processed to a higher contrast than is the ON.

5. The Dupe is usually examined at magnification below that needed to observe its maximum resolution potential. *but not always*

All of these properties indicate a need for specific experimentation on the image quality of the Dupe emulsion. Studies to be done in Phase 2 would include the following:

1. Study the relationship between the morphology of the developed silver of the ON (as a function of density and line frequency) and the image quality of the duplicate positive of this imagery.

2. Study the effect of grain morphology, GSD, sensitization, and spectral response of the duplicate positive emulsion and its ability to record the ON.

Experimentally, our approach will be to study duplication by the methods of emulsion preparation, coating, and processing, using the optical and electron microscope for observation, and the MTF or AIM curve as the image criteria.

Work Statement for Phase 2 — The Chemistry Department of [redacted] 25X1
[redacted] proposes to make available the personnel and laboratory 25X1
facilities needed to perform a major program on the relationship between the parameters of the photographic emulsion and its processing, and the image quality of the final processed original and duplication images.

1. We propose to study, in depth, the effect on image quality of experimentally varied emulsion parameters:

   a. Effect of grain size distribution and mean grain area

   b. Effect of grain morphology

   c. Effect of emulsion thickness and coverage

   d. Effect of developer type and the resultant morphology of the developed silver as a function of density and of line frequency

   e. Effect of emulsion gelatin, chemical sensitization, and spectral sensitization.

   Our image evaluation criteria will be MTF and AIM curve analyses as they may be modified by work performed on other phases of this program. Our measurement tools will be optical and electron microscopy, sensitometric procedures, and other needed optical and mechanical techniques.

2. We propose to study in depth the relationship between the developed emulsion parameters of the ON and the final image quality of experimentally prepared model duplication emulsions. We shall study:

   a. The effect of ON developed silver structure on the Dupe as a function of ON density and line frequency;

   b. The effect of the grain size distribution, average grain size, thickness, coverage, and sensitization of the Dupe emulsion on the quality of the final Dupe.

   The image quality of the final Dupe may be determined in in terms of MTF and AIM curves, or in terms of interpretative parameters to be developed on other phases of the program.

Phase 3 (January 1968 - 1971)

In Phase 3 of this program, we shall attempt to fulfill the general goals described in detail in the opening section of this proposal. The experimental procedures will be those of the variation of emulsion and processing parameters in conformance with the mathematical models of the photographic emulsion and of image quality that will have been arrived at in later stages of the program. In the advanced stages of the program, the model emulsions will be simulations of fine grain films such as 3404, 5427, and 8430, and may in fact be superior at least in some aspects of image quality. Also, processing solutions formulated later in the program may represent advances over the state of the art, particularly, with respect to the latitude of high resolution development, a subject we are now investigating under another contract.

Evaluation of the model emulsions will be done by new image evaluation methods that may become available to us as a result of parallel work on the overall program. Recommendations for improved performance on existing materials, and the submission of improved materials (emulsions, developers, exposure and duplication methods) will be a part of the conclusion of the proposed program.

OPTICS

Proposed Program

Task 1: Theoretical and Experimental Investigation of Conditions for Linearity

Meaningful quantitative measurements can be made on an image intensity distribution to relate that image to the object only when the optical imaging system which generates the image is linear in intensity. The first part of our proposed program is therefore a theoretical and experimental investigation of the conditions for which optical imaging systems may be regarded as linear in intensity. This study will apply to microdensitometers, projectors, and viewing systems such as microscopes.

There are three situations in which the theory of partial coherence indicates that the imaging system may be regarded as linear in intensity. These situations are characterized by the conditions that (1) the coherence interval of the object illumination be much less than the characteristic width of the lens diffraction pattern in object space, (2) the object transparency be of constant phase and low contrast, and (3) the object structure be slowly varying over a distance comparable to the coherence interval of the object illumination. The first of these conditions

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was evident in the imaging calculations for sine waves and edges which were presented in the proposal for the first year program (i.e., Proposal No. TO-B 100-65). A treatment of the second and third conditions follows. While the first of these three conditions may be regarded as the most general since it makes no assumption about the form of the object transmittance, the second or third conditions may apply in particular situations where the first does not apply. A review of the general theory of partial coherence as it applies to image analysis is contained in the proposal for the first year program. The following discussion of conditions (2) and (3) is reviewed here only to provide a basis for discussing the proposed work for the continuation program.

Low-Contrast Objects — For simplicity, we consider a one-dimensional system, unit magnification, and a single lens aperture. The object transparency is in the ξ plane and the image in the x plane. The mutual intensity in the image plane is then

$$\Gamma_i\left(x_1, x_2\right) = \iint \Gamma_o\left(\xi_1, \xi_2\right) t\left(\xi_1\right) t^*\left(\xi_2\right) K\left(x_1 - \xi_1\right) K^*\left(x_2 - \xi_2\right) d\xi_1 d\xi_2 , \tag{2-1}$$

where $\Gamma_o\left(\xi_1, \xi_2\right)$ is the mutual intensity of the radiation incident on the object, $t(\xi)$ is the complex amplitude transmittance of the object (which we take to be of constant phase), and $K(x-\xi)$ is the complex amplitude impulse response of the system.

Since Eq. (2-1) contains the product tt^*, the constant phase cancels. We may then take t to be real, i.e. $t = t^*$. We represent a low contrast object by

$$t(\xi) = t_o + t'(\xi) , \tag{2-2}$$

where t_o is a constant and

$$t'(\xi) \ll t_o \quad . \tag{2-3}$$

Then we have

$$t(\xi_1)\, t^*(\xi_2) = t(\xi_1)\, t(\xi_2) = [\, t_o + t'(\xi_1)]\, [\, t_o + t'(\xi_2)]$$

$$\cong t_o^2 + t_o [\, t'(\xi_1) + t'(\xi_2)] \quad , \tag{2-4}$$

where we have used Eq. (2-3) to obtain Eq. (2-4). We note for later reference that the intensity distribution in the object from Eq. (2-4) is

$$I(\xi) = |t(\xi)|^2 \cong t_o^2 + 2t_o t'(\xi) \quad . \tag{2-5}$$

Using Eq. (2-4) in Eq. (2-1), we find

$$\Gamma_i(x_1, x_2) = \iint \Gamma_o(\xi_1, \xi_2) \left\{ t_o^2 + t_o [\, t'(\xi_1) + t'(\xi_2)] \right\}$$

$$K(x_1 - \xi_1)\, K^*(x_2 - \xi_2)\, d\xi_1\, d\xi_2 \quad . \tag{2-6}$$

The intensity in the image plane is, from Eq. (2-6),

$$I_i(x) = \Gamma_i(x, x) = t_o^2 \iint \Gamma_o(\xi_1, \xi_2)\, K(x - \xi_1)\, K^*(x - \xi_2)\, d\xi_1\, d\xi_2$$

$$+ t_o \iint \Gamma_o(\xi_1, \xi_2)\, t'(\xi_1)\, K(x - \xi_1)\, K^*(x - \xi_2)\, d\xi_1\, d\xi_2$$

$$+ t_o \iint \Gamma_o(\xi_1, \xi_2)\, t'(\xi_2)\, K(x - \xi_1)\, K^*(x - \xi_2)\, d\xi_1\, d\xi_2 \quad , \tag{2-7}$$

where we set $x_1 = x_2 = x$.

It is clear that the variables ξ_1 and ξ_2 are dummy variables in the integrations of Eq. (2-7), and so we may interchange ξ_1 and ξ_2 in the second term of (2-7) to obtain

$$I_i(x) = t_o^2 \iint \Gamma_o(\xi_1, \xi_2)\, K(x - \xi_1)\, K^*(x - \xi_2)\, d\xi_1\, d\xi_2$$

$$+ t_o \int t'(\xi_2) \left\{ \int [\Gamma_o(\xi_2, \xi_1)\, K(x - \xi_2)\, K^*(x - \xi_1)\right.$$

$$\left. + \Gamma_o(\xi_1, \xi_2)\, K(x - \xi_1)\, K^*(x - \xi_2)]\, d\xi_1 \right\} d\xi_2 \ . \qquad (2\text{-}8)$$

Now note that we have

$$\Gamma(\xi_2, \xi_1) = \Gamma^*(\xi_1, \xi_2) \ . \qquad (2\text{-}9)$$

Clearly, when

$$K(x - \xi) = K^*(x - \xi) \qquad (2\text{-}10)$$

and

$$\Gamma_o(\xi_1, \xi_2) = \Gamma_o^*(\xi_1, \xi_2) \ , \qquad (2\text{-}11)$$

(i.e., when both the amplitude impulse response and the mutual intensity of the object illumination are real) by using Eqs. (2-9), (2-10), and (2-11) in the second term of Eq. (2-8) we find that

$$\int \Gamma_o(\xi_2, \xi_1)\, K(x - \xi_2)\, K^*(x - \xi_1)\, d\xi_1 = \int \Gamma_o(\xi_1, \xi_2)\, K(x - \xi_1)\, K^*(x - \xi_2)\, d\xi \ . \qquad (2\text{-}12)$$

Then Eq. (2-8) becomes

$$I_i(x) = \int I_o(\xi_2)\, G(x, \xi_2)\, d\xi_2 \ , \qquad (2\text{-}13)$$

where from Eq. (2-5)

$$I_o(\xi_2) = t_o^2 + 2t_o t'(\xi_2) \tag{2-14}$$

is the intensity distribution in the object, and

$$G(x, \xi_2) = K(x - \xi_2) \int \Gamma_o(\xi_1, \xi_2)\, K(x - \xi_1)\, d\xi_1 \tag{2-15}$$

is the Green's function or intensity impulse response of the system.

Equation (2-13) represents a system linear in intensity. Examination of Eq. (2-8) shows that Eqs. (2-9) and (2-10) are sufficient conditions, rather than necessary ones, for Eq. (2-13). The necessary condition is actually Eq. (2-12). The conditions of Eqs. (2-10) and (2-11) are realistic and are satisfied to a good approximation by the present system.

In the important practical case when the mutual intensity of the radiation incident on the object plane is spatially stationary, then we have

$$\Gamma_o(\xi_1, \xi_2) = \Gamma_o(\xi_1 - \xi_2) \tag{2-16}$$

and Eq. (2-15) becomes

$$G(x, \xi_2) = K(x - \xi_2) \int \Gamma_o(\xi_1 - \xi_2)\, K(x - \xi_1)\, d\xi_1 \ . \tag{2-17}$$

Now make the change of variables

$$\xi = \xi_1 - \xi_2 \tag{2-18}$$

in Eq. (2-17) so that

$$\begin{aligned} G(x, \xi_2) &= K(x - \xi_2) \int \Gamma_o(\xi)\, K\left[(x - \xi_2) - \xi\right] d\xi \\ &= K(x - \xi_2)\, f(x - \xi_2) \ , \end{aligned} \tag{2-19}$$

where

$$f(x - \xi_2) = \int_{-\infty}^{\infty} \Gamma_o(\xi)\, K\left[(x - \xi_2) - \xi \right] d\xi \ .$$

The conclusion from Eq. (2-19) is that

$$G(x, \xi_2) = G(x - \xi_2) \qquad (2\text{-}20)$$

and therefore the intensity impulse response, or Green's function, of the system is spatially stationary.

The spatial frequency domain description of the system is then obtained by using Eq. (2-20) in Eq. (2-13) to obtain

$$I_i(x) = \int I_o(\xi_2)\, G(x - \xi_2)\, d\xi_2 \ , \qquad (2\text{-}21)$$

and taking the spatial Fourier transform of Eq. (2-21), we then have

$$\tilde{I}_i(\nu) = \tilde{I}_o(\nu)\, T_{pc}(\nu) \ , \qquad (2\text{-}22)$$

where $T_{pc}(\nu)$ is the intensity modulation transfer function of the partially coherent imaging system. The quantities $\tilde{I}_i(\nu)$ and $\tilde{I}_o(\nu)$ are the Fourier transforms of the image and object intensity distributions respectively.

The definition of $T_{pc}(\nu)$ is

$$T_{pc}(\nu) = \frac{\int_{-\infty}^{\infty} G(\xi)\, e^{2\pi i \xi \nu}\, d\xi}{\int_{-\infty}^{\infty} G(\xi)\, d\xi} \ , \qquad (2\text{-}23)$$

where we have normalized so that $T_{pc}(0) = 1$.

[redacted]

We shall now evaluate $T_{pc}(\nu)$ for the elementary case of a rectangular incoherent slit-source and a rectangular lens aperture. The source is in the β plane; the other planes are as in Eq. (2-1). The halfwidth of the rectangular source is b and that of the rectangular lens aperture is a. Magnification is unity. We assume that the size of the source is much less than its distance from the object plane.

The mutual intensity of the illumination incident on the object, from the van Cittert-Zernike theorem (Eq. (2-8)), is

$$\Gamma_o(\xi_1 - \xi_2) = \int_{-\infty}^{\infty} I(\gamma)\, e^{-2\pi i\gamma(\xi_1 - \xi_2)}\, d\gamma \quad , \qquad (2\text{-}24)$$

where

$$\gamma = \frac{\beta}{\lambda R} \quad , \qquad (2\text{-}25)$$

and the intensity distribution of the source is given by

$$I(\gamma) = \left\{ \begin{array}{ll} 1 & |\gamma| \leq \dfrac{b}{\lambda R} \\ 0 & |\gamma| > \dfrac{b}{\lambda R} \end{array} \right\} . \qquad (2\text{-}26)$$

A Fourier transform relation also holds between the lens aperture and the amplitude impulse response of the lens. Thus we have

$$K(\xi) = \int_{-\infty}^{\infty} A(\eta)\, e^{-2\pi i\eta\xi}\, d\eta \quad , \qquad (2\text{-}27)$$

where

$$\eta = \frac{\alpha}{\lambda S} \quad , \qquad (2\text{-}28)$$

[redacted]

and the amplitude transmittance of the lens aperture is given by

$$A(\eta) = \begin{Bmatrix} 1 & |\eta| \leq \dfrac{a}{\lambda S} \\ 0 & |\eta| > \dfrac{a}{\lambda S} \end{Bmatrix} \tag{2-29}$$

Now using Eqs. (2-19) and (2-23), we find that $T_{pc}(\nu)$ has the form

$$T_{pc}(\nu) = \frac{\displaystyle\int_{-\infty}^{\infty} K(\xi) \left[\int_{-\infty}^{\infty} \Gamma_o(\xi')\, K(\xi - \xi')\, d\xi' \right] e^{2\pi i \xi \nu}\, d\xi}{\displaystyle\int_{-\infty}^{\infty} K(\xi) \left[\int_{-\infty}^{\infty} \Gamma_o(\xi')\, K(\xi - \xi')\, d\xi' \right] d\xi} . \tag{2-30}$$

Using the convolution theorem on the inner integrals in numerator and denomintor of Eq. (2-30), we have

$$T_{pc}(\nu) = \frac{\displaystyle\int_{-\infty}^{\infty} K(\xi) \left[\int_{-\infty}^{\infty} \tilde{\Gamma}_o(\nu')\, \tilde{K}(\nu')\, e^{-2\pi i \xi \nu'}\, d\nu' \right] e^{2\pi i \xi \nu}\, d\xi}{\displaystyle\int_{-\infty}^{\infty} K(\xi) \left[\int_{-\infty}^{\infty} \tilde{\Gamma}_o(\nu')\, \tilde{K}(\nu')\, e^{-2\pi i \xi \nu'}\, d\nu' \right] d\xi} \tag{2-31}$$

$$= \frac{\displaystyle\int_{-\infty}^{\infty} \tilde{\Gamma}_o(\nu')\, \tilde{K}(\nu') \left[\int_{-\infty}^{\infty} K(\xi)\, e^{2\pi i \xi (\nu - \nu')}\, d\xi \right] d\nu'}{\displaystyle\int_{-\infty}^{\infty} \tilde{\Gamma}_o(\nu')\, \tilde{K}(\nu') \left[\int_{-\infty}^{\infty} K(\xi)\, e^{-2\pi i \xi \nu'}\, d\xi \right] d\nu'} \tag{2-32}$$

$$= \frac{\displaystyle\int_{-\infty}^{\infty} \tilde{\Gamma}_o(\nu')\, \tilde{K}(\nu')\, \tilde{K}(\nu - \nu')\, d\nu'}{\displaystyle\int_{-\infty}^{\infty} \tilde{\Gamma}_o(\nu')\, \tilde{K}(\nu')\, K(-\nu')\, d\nu'} . \tag{2-33}$$

We can evaluate Eq. (2-33) with Eqs. (2-24) through (2-29). The variables $a/\lambda S$ and $b/\lambda R$ are the usual diffraction variables that arise in problems of this type. We shall therefore redefine them to be

$$a' = \frac{a}{\lambda S} \qquad \text{and} \qquad b' = \frac{b}{\lambda R} \quad .$$

The evaluated form of $T_{pc}(\nu)$ is then for $\nu \geq 0$,

$$T_{pc}(\nu) = \begin{cases} 0 & \nu > 2a' \text{ or } \nu > a' + b' \\ 1 & a' > b' \text{ and } 0 \leq \nu \leq a' - b' \\ 1 - \dfrac{\nu}{a' + b'} & a' > b' \text{ and } a' - b' < \nu \leq a' + b' \\ 1 - \dfrac{\nu}{2a'} & a' \leq b' \text{ and } 0 \leq \nu \leq 2a' \end{cases} \tag{2-34}$$

Using Eqs. (2-23) and (2-19) we can easily show that by a change of variables

$$T_{pc}(\nu) = T_{pc}(-\nu) \quad . \tag{2-35}$$

Then Eqs. (2-34) and (2-35) define $T_{pc}(\nu)$. It is clear that $T_{pc}(\nu)$ is real, i.e.,

$$T_{pc}(\nu) = T^{*}_{pc}(\nu) \quad . \tag{2-36}$$

Figure 2-1(a) shows Eq. (2-34) for various ratios M of a' to b'. A similar calculation for the case of a circular source and circular lens aperture is shown in (b) of Figure 2-1 for various ratios ϵ of the radius of the lens to the radius of the source.

<u>Objects With Low Spatial Frequency Content</u> — Another case in which the partially coherent imaging system is completely characterized by an intensity impulse response or its Fourier transform — the intensity modulation transfer function — is that of objects having low spatial frequency content. Figure 2-2 is an example of such an object; here the object structure $t(\xi)$

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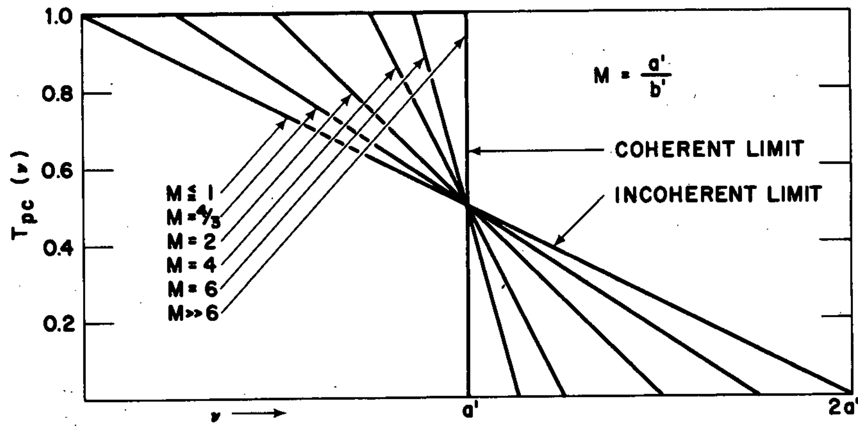
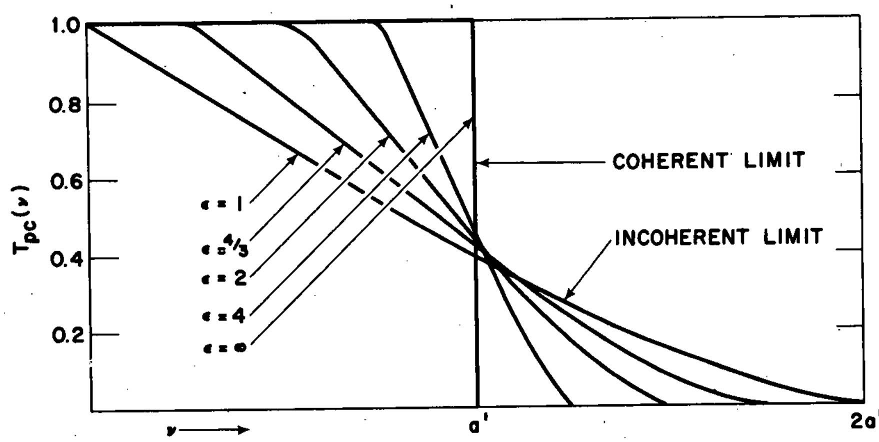


a. Cylindrical Lens



b. Spherical Lens

Figure 2-1. Transfer Functions for Ideal Lens Imaging Low Contrast Objects with Partially Coherent Illumination

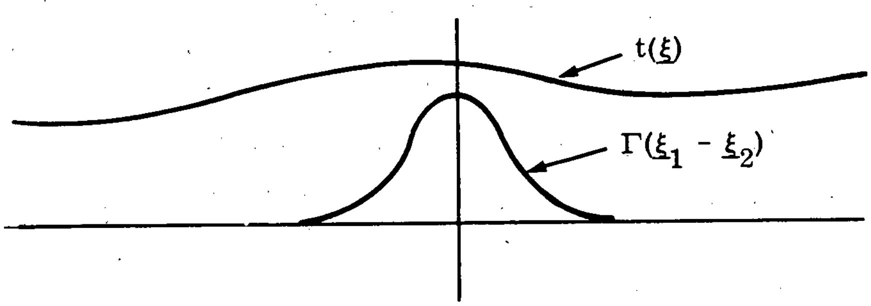


Figure 2-2. Slowly Varying Object $t(\xi)$ vs Mutual Intensity Function $\Gamma(\xi_1 - \xi_2)$

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varies slowly over distances in which the mutual intensity function $\Gamma(\underline{\xi}_1 - \underline{\xi}_2)$ is nonzero.

Using the general imaging equation ((18) in Chap. 2),

$$I(\underline{x}) = \iint \Gamma(\underline{\xi}_1 - \underline{\xi}_2)\, t(\underline{\xi}_1)\, t^*(\underline{\xi}_2)\, K(\underline{x} - \underline{\xi}_1)\, K^*(\underline{x} - \underline{\xi}_2)\, d\underline{\xi}_1\, d\underline{\xi}_2 \quad , \qquad (2\text{-}37)$$

and letting $\underline{\xi}_1 - \underline{\xi}_2 = \underline{\sigma}$, we have

$$I(\underline{x}) = \iint \Gamma(\underline{\sigma})\, t(\underline{\xi}_2 + \underline{\sigma})\, t^*(\underline{\xi}_2)\, K(\underline{x} - \underline{\sigma} - \underline{\xi}_2)\, K^*(\underline{x} - \underline{\xi}_2)\, d\underline{\xi}_2\, d\underline{\sigma} \quad . \qquad (2\text{-}38)$$

Now when the changes in $t(\underline{\xi}_2 + \underline{\sigma})$ are small in the distance $\underline{\sigma}$ over which $\Gamma(\underline{\sigma})$ is nonzero, we may make the approximation that

$$t(\underline{\xi}_2 + \underline{\sigma}) \cong t(\underline{\xi}_2) \quad . \qquad (2\text{-}39)$$

If we then use Eq. (2-39), Eq. (2-38) becomes

$$I(\underline{x}) = \int t(\underline{\xi}_2)\, t^*(\underline{\xi}_2) \left\{ K^*(\underline{x} - \underline{\xi}_2) \int \Gamma(\underline{\sigma})\, K\left[(\underline{x} - \underline{\xi}_2) - \underline{\sigma} \right] d\underline{\sigma} \right\} d\underline{\xi}_2 \quad . \qquad (2\text{-}40)$$

Therefore, we have

$$I(\underline{x}) = \int I(\underline{\xi}_2)\, G(\underline{x} - \underline{\xi}_2)\, d\xi_2 \quad , \qquad (2\text{-}41)$$

which is a linear intensity superposition integral in which

$$G(\underline{x} - \underline{\xi}_2) = K^*(\underline{x} - \underline{\xi}_2) \int \Gamma(\underline{\sigma})\, K\left[(\underline{x} - \underline{\xi}_2) - \underline{\sigma} \right] d\underline{\sigma} \qquad (2\text{-}42)$$

is the intensity impulse response of the system.

Interestingly enough, Eq. (2-42) has the same form as Eq. (2-19) when $K(x - \underline{\xi})$ is real. For this case, then, the transfer functions shown in Figure 2-1 will apply to Eq. (2-41). A significant feature of the resultant intensity modulation transfer function curves shown in Figure 2-1 is that the transfer function is flat, i.e., there is no reduction in the modulation of the spatial frequency components, out to some critical frequency which is determined by the relative size of the coherence interval of the object illumination and the lens diffraction pattern in object space.

Work Statement for Task 1 — On the basis of the above considerations we shall investigate both theoretically and experimentally:

1. The relationship between the coherence interval of the object illumination and the size of the imaging system diffraction pattern in object space as it affects the assumption that an imaging system is linear in intensity. We shall assume partially coherent quasi-monochromatic object illumination and diffraction limited optics. The experiments which are performed in this investigation will be designed to represent the conditions assumed in the theory, when the theory shows a linear relationship between object intensity and image intensity.

2. How low the contrast of an object must be in order that the assumption that an imaging system is linear in intensity be justified.

3. The relationship between the spatial frequency content of an object and the coherence interval of the object illumination to provide a general criterion from which one can determine the validity of the assumption of linearity.

Task 2: Measurements of Degree of Coherence of Illumination in Sponsor Equipment

The second part of our proposed program consists of actual measurements of the degree of coherence of the illumination in precision viewing, copying, and analyzing systems now in use at the Sponsor's location. This includes viewers, projectors, light tables, and microdensitometers. These measurements would be designed to determine to what extent the assumption that these imaging systems are linear in intensity is justified and, therefore, to what extent reliable and meaningful quantitative measurements can be made on the intensity distribution in the images they produce.

Viewing and Projecting Systems — Since optical viewing and projecting systems are not designed with the coherence of the illumination in mind, it cannot be presumed that any such systems are linear in intensity. Particularly, where high resolutions are involved coherence intervals on the order of a few wavelengths can produce noticeable effects.

Illuminating systems for viewers and projectors are basically designed to produce uniform illumination across the field of view at a fairly high intensity. The required intensity with which the sample must be illuminated depends on the characteristics of the imaging system and the sensitivity of the final detector. In a microdensitometer used at high resolution, for example, where the sample is greatly magnified and a narrow scanning slit is used, the illumination of the sample must be intense enough to cause the photomultiplier to operate above its dark noise level. Attaining this condition is often a problem even with conventional illuminating systems. In viewing systems in which the human eye is the final component, the illumination must be intense enough to be comfortably detected by the eye. In some cases, particularly where quantitative measurements at high spatial frequencies are required, it is necessary to use an imaging system which is linear in intensity. Such a system would add the criterion of incoherent illumination, or at least illumination where the coherence interval is much smaller than the variations in the object, to those of uniform and intense illumination.

Light Tables. – The most "incoherent" type of viewing system in normal use is a light table, which usually consists of an array of fluorescent lamps behind an opal glass diffuser, on which the sample is placed. It is well known that a stationary diffuser does not affect the coherence of radiation propagating through it. In order to attain uniform illumination over the surface of the table, the fluorescent lamps are set back several inches from the opal glass. Again, we have the familiar case of light from an incoherent source propagating over a certain distance, thus becoming partially coherent, and then being used to illuminate a transparency which is subsequently imaged.

Microdensitometers – As we have seen, condenser systems do not produce incoherent illumination. A sample can be "incoherently" illuminated only if it is illuminated by an extended incoherent source directly behind the sample or if the coherence of partially coherent illumination is reduced by using a moving random scatterer directly behind the object. This can be accomplished by ensemble averaging the mutual intensity over many configurations of a random scatterer. Rapidly moving ground glass, milk, and colloidal gold solutions are often used as such scatteres. In the case of ground glass, it was shown under [redacted] 25X1

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Task Order No. 3 that the coherence of the light resulting from a piece of rotating ground glass illuminated by a He-Ne laser beam could be characterized by assuming that the ground glass acted as an incoherent source.

In a system such as a microdensitometer, where only a small area of the sample need be illuminated at one time, the type of illumination in which the coherence is reduced by a moving random scatterer will undoubtedly provide higher intensity illumination than can be conveniently attained with an extended incoherent source directly behind the object.

Coherence problems can also arise in other types of precision viewing and projecting systems. Common instruments of this type use various light sources and condenser systems, and we can expect to find large differences in the degree of coherence of the light in the object plane in a sampling of such instruments.

Work Statement for Task 2 — Under the first year contract a theoretical and experimental determination is being made of the degree of coherence in the object plane of a Joyce-Loebl microdensitometer. We propose to extend this type of analysis to other types of optical viewing, analyzing, and projecting systems in use at the Sponsor's location.

We shall investigate experimentally the coherence of the illumination in light tables, microdensitometers, enlargers, and other special types of analyzing systems in use at the Sponsor's facility. Where feasible such tests will be conducted by making two pinhole interferometer measurements of the degree of coherence. For smaller coherence intervals the coherence will be determined by such techniques as observation of the form of the diffraction pattern from extremely small apertures or comparison of images of certain test objects with images predicted for known degrees of coherence.

Task 3: Design Concepts for Linearized Systems

The proposed work for tasks 1 and 2 of this program involves a theoretical and experimental determination of the conditions under which optical imaging systems may be regarded as linear in intensity, and an experimental determination of the applicability of these conditions to precision analyzing equipment now in use at

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the Sponsor's facility. Task 3 of this proposed program will be the formation of design concepts for the corresponding linearized systems. These design concepts will incorporate the conclusions reached under Task 1 and the awareness of the state of the art in currently used instrumentation obtained under Task 2.

Work Statement for Task 3 — Under this part of the program we shall:

1. Determine design concepts for linearized microdensitometers, light tables, enlargers, and microscope viewing systems. The use of both lasers and conventional light sources for such an application will be studied. Particular attention will be paid to attaining the maximum intensity for the required coherence intervals.

2. Conduct experimental tests of these design concepts to determine their feasibility for actual application. This will be done by forming images on an optical bench imaging system under the conditions prescribed by the design concept.

Task 4: Theoretical and Experimental Investigation of Particular Coherence Problems

Determination of Object Intensity from Γ_{12} in Image — The problem of determining the object from a knowledge of the image cannot, in general, be solved. This is because any imaging system has a finite aperture. However, the "principal part" of the object spectrum, i.e. the object spectrum up to some $|\mu|$ max, can be found when the imaging system is characterized by a transfer function. For partially coherent illumination the imaging system may be regarded as linear in the mutual spectral density and the transfer function is then the generalized transfer function $\mathcal{L}(\mu_1, \mu_2, \nu)$ defined by

$$\mathcal{L}\left(\mu_1, \mu_2, \nu\right) = \frac{\overset{o}{\Gamma}_i\left(\mu_1, \mu_2, \nu\right)}{\overset{o}{\Gamma}_o\left(\mu_1, \mu_2, \nu\right)}, \qquad (2\text{-}43)$$

where $\overset{o}{\Gamma}(\mu_1, \mu_2, \nu)$ is the spatial and temporal Fourier transform of the mutual coherence function and the subscripts i and o denote image and object space

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respectively. It is shown by Beran and Parrent* that this generalized transfer function is related to the amplitude impulse response by the relation

$$\mathcal{L}\left(\mu_1, \mu_2, \nu\right) = \tilde{K}\left(\mu_1, \nu\right) = \tilde{K}^*\left(-\mu_2, -\nu\right) , \qquad (2\text{-}44)$$

where $K(\nu)$ is the amplitude impulse response for the particular temporal frequency ν and the tilde denotes a spatial Fourier transform.

For quasi-monochromatic illumination the temporal frequency notation ν may be dropped. The theory then shows that the "principal part" of the spatial Fourier transform of the object mutual intensity may be found by dividing the spatial Fourier transform of the image mutual intensity distribution by the generalized transfer function of the imaging system, i.e.,

$$\tilde{\Gamma}_o\left(\mu_1, \mu_2\right) = \frac{\tilde{\Gamma}_i\left(\mu_1, \mu_2\right)}{\mathcal{L}\left(\mu_1, \mu_2\right)} \quad . \qquad (2\text{-}45)$$

The intensity in the object, which is the quantity of interest in image evaluation, is then a reduced form of the object mutual intensity distribution which has been determined in this way.

Detection at Low Contrast — It has been shown under Task 1 that when the object transparency is of low contrast the imaging system may be regarded as linear in intensity. Under these conditions, however, the transfer function is not that usually found for a system linear in intensity (i.e., the convolution of the aperture function with itself) but has the form shown in Figure 2-1. When the object illumination is coherent, the transfer function which applies is that shown for $\epsilon = \infty$ and $m = \infty$. The sharp cutoff in spatial frequency shown by these curves produces the usual ringing effect in imaging of objects with high spatial frequency content such as edges. Thus, under these conditions the system is linear in

*M. J. Beran and G. B. Parrent, Jr., "Theory of Partial Coherence" (Englewood Cliffs, N. J.: Prentice Hall, Inc., 1964).

intensity and there is still enhancement of edges. This use of coherent illumination with low contrast objects may be expected to increase the probability for detection of edges and, therefore, deserves investigation as a tool for use by photointerpreters.

Coherence Effects with Color Transparencies — When a transparency is illuminated with white light it may be possible to make the quasi-monochromatic approximation and obtain reliable predictions of the coherence effects to be expected in imaging. In some circumstances, however, such as the white light illumination of color transparencies, this approximation may mask important effects due to the division of the spectral transmittance of the transparencies into several distinct bands. The coherence effects in image evaluation involving these color transparencies should be investigated as a practical application of the polychromatic theory.

Stereo Problems — In stereo viewing, two images of the same object taken from a slightly different perspective are imaged separately through the two eyes of the photointerpreter and are then superimposed to give a three-dimensional effect. Since light table illumination is usually used in such viewing, coherence effects may be expected to arise. We therefore propose to investigate the effects of coherent illumination and nonlinear imaging on stereo viewing. Both light table illumination and more coherent illumination will be considered.

Work Statement for Task 4 — We shall:

1. Investigate the feasibility of obtaining the principal part of the object intensity distribution from the mutual intensity distribution in the image. This work will assume partially coherent quasi-monochromatic object illuminations and ideal diffraction limited lenses. We shall find the mutual intensity distribution in the image of selected simple object such as edges by suitable theoretical methods. A computer calculation will then perform the process of division by the generalized transfer function to determine the object mutual intensity distribution. The predicted intensity distribution will be obtained as a reduced form of this object mutual intensity. The predicted intensity will then be compared directly with the actual intensity distribution of the object which was imaged.

2. Investigate the use of coherent object illumination to increase the probability of detection of low contrast objects such as edges. This work will employ quasi-monochromatic light. The relation between the contrast at which the probability of detection is significantly increased, and the contrast at which the system may be regarded as linear in intensity (see Task 1), will be determined. The lower of these two contrast values will determine the upper limit for contrast values when it is desirable to use coherent light and still make reliable quantitative measurements on the image intensity distribution.

3. Investigate those partial coherence problems which are involved in the white light analysis of transparencies which have transmittance values in different spectral regions and for which the quasi-monochromatic approximation is not justified. This work will be both theoretical and experimental and will assume diffraction limited imaging optics.

4. Investigate the effects peculiar to stereo viewing which arise from the degree of coherence of the object illumination. The coherence of the illumination in currently active instrumentation such as viewers and light tables will be taken into account in providing estimates of the effects to be expected.

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GRAIN STUDIES

In our present program of grain studies we are trying out new procedures to enable us to predict the image formation in a photographic film when the light distribution in the aerial image, which produces the photographic image, is given. Although this might seem unimportant to the user of the photographic images, a better understanding of these phenomena will lead to better imagery, which is important, and also a better understanding of this area will lead to improved interpretation of the existing images and in all probability will lead to better methods of looking at these images.

Since the problem is extremely complicated, and since entirely new approaches are used, our present program is twofold:

(1) Improve the mathematical description of the models on which image formation is built

(2) Verify experimentally the theoretical results obtained to date.

In order to minimize experimental errors and use emulsions which come as close as possible to representing the models on which the theory is based, special emulsions are used in this program. The details of this program are covered in our Work Statement and in our reports. This work should be continued.

During the period covered in this proposal, special attention should be given to the following areas.

(a) Film grains are not all equally sensitive to light. Larger grains have a larger sensitivity to light and, therefore, the grain size distribution will differ for different densities. In our present models this is not taken into consideration.

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(b) The situation in which the light distribution in the image-forming bundles is asymmetric is very important. The problem of resolving such images is extremely difficult - but extremely important, since only on the axial point of the image formed by a lens can one expect symmetry in the image. The imagery of most of the area covered, therefore, is usually asymmetric. Our present feeling is that this kind of imagery can be predicted with our present theory. Again, this should be followed-up with experimental verification.

(c) Our present studies are based on a model of the photographic emulsions. In many fields of science it is often not necessary to know the exact mechanism underlying the phenomena in order to predict the experimental results. For instance, one can predict the behaviour of most gasses by the law of Boyle-Gay-Lussac without ever referring to atomistic arguments, although this law follows directly from the assumption that gasses consist of a cloud of molecules. It is important to note here that deviations in behaviour from this law by actual gasses are more easily understood by the molecular theory and, therefore, more easily predicted, and its proper mathematical treatment more easily described.

The same can be done for our grainy images. One could conceivably find the mathematical description of the law governing image formation without ever having a model to base the theory on. However, these models will be of great help in understanding the phenomena and in finding the proper form of the mathematical formula to describe these phenomena. For actual film the models become very complicated; therefore, we propose that parallel to the understanding of the phenomena, we try to formulate the laws governing the image formation on actual films. No matter how complicated the actual film is, there are only a few basic phenomena that occur: the grain size distribution, the sensitivity of the grains, the random distribution of the grains when not all grains are exposed and developed, and the scattering of light between the various layers of grain. In our opinion, enough is known to formulate the type of mathematical form that will describe the image-forming properties in terms of measurable quantities on the film.

[redacted] 25X1

(d) In our work we will also cover the phenomena that the image of an edge will not always be formed where the edge originally was located. In the mensuration program it becomes important to understand these phenomena to insure better interpretation of the measured data. For instance, from our present work it follows that the measured location of an edge is influenced by the density levels on both sides of the edge.

may not be a realistic measure of image

The Calculation of Partially Coherent Image Formation in the Presence of Aberrations

I. Introduction

The problem of partially coherent image formation arises in a number of important applications. viz microdensitometers, lens-testing equipment, viewer systems, etc. Although calculations have been performed for lens systems free from aberrations, for systems with small aberrations, up to a few waves, very little information is available. We feel that important advances in the design of equipment of the type mentioned above can only be realized after this gap in the literature has been filled.

II. Technical Approach

In order to arrive at realistic results, it is necessary to take a pragmatic attitude towards the definition of objects and images. Transparent objects will be described by their intensity transmission, and, if required, a phase function. Both these quantities may be considered measurable. Furthermore, any intensity modulation in the image plane that can be tracked back to the object will be called an image.

harmonic — generation due to coherence

It will also be necessary to describe the aberrations of the lens system in a form intelligible to both the physicist and the lens designer. We propose to employ eikonal function theory, which is eminently suited to tie together the various aspects of image formation.

In the initial phases of the study it will be necessary to make various restricting assumptions. We mention:

[redacted] approach — different from general 25X1
— should provide an interesting and important contrast in method rationale and

[redacted] 25X1

perhaps results.

1. The quasi-monochromatic approximation will be used throughout. This is not a serious limitation as the path differences to be considered will always be small. The more general case can then be derived from the quasi-monochromatic case by summation, provided that the relevant power spectra are sufficiently smooth.

2. It will be assumed that the (finite) transparent object is illuminated by an infinite plane in which the mutual intensity satisfies the condition of spatial stationarity:

$$\Gamma\left(x_1, y_1, x_2, y_2\right) = \Gamma\left(x_1 - x_2, y_1 - y_2\right) .$$

This assumption is not absolutely necessary, but is physically acceptable. It has the considerable advantage that the Fourier transform of Γ takes a particularly simple form:

$$1/\lambda^4 \iiiint dx_1\, dy_1\, dx_2\, dy_2\; e^{-ik[L_1x_1 + M_1y_1 - L_2x_2 - M_2y_2]}\, \Gamma\left(x_1, y_1, x_2, y_2\right)$$

$$= \hat{\Gamma}\left(L_1, M_1, L_2, M_2\right)$$

$$= E\left(L_1, M_1\right)\; \delta\left(L_1 - L_2\right)\; \delta\left(M_1 - M_2\right) .$$

The function E is closely related to the radiation pattern of the source plane, which is a physically attractive feature of this model.

3. For reasons of expediency, the initial phases of the study will be limited to the two-dimensional rather than the full three-dimensional case. This restriction will be dropped after sufficient insight into the phenomenae has been gained.

4. In the initial phases of the study an attempt will be made to solve at least a few cases analytically. The experience gained in this work will be of substantial aid in the construction of computer programs that can be used to solve more realistic cases.

5. In order to obviate the well known difficulties due to the mix-up of the transmission and the phase characteristics of the object, only objects whose transmission exceeds everywhere some small positive number will be considered. This restriction can be removed in later stages of the work by a limiting procedure.

Temperature Variations in Optical Systems

Much work has been done on the effect of differences in temperature on the performance of optical systems. Most of this work has been performed to enable us to predict performance of systems in temperature equilibrium at different temperatures. In general, a properly built optical system will not deteriorate the image quality very much when the system is in temperature equilibrium at various temperature levels. The major effect is a shift in the focal plane with temperature. The situation is entirely different during the period in which the system goes from one temperature to the next. The behaviour of an optical system, then, is dependent on many complicated phenomena, and during this transition period the image will always deteriorate. One very important fact to note here is that from theoretical considerations and from practical experience with various optical systems, it is known that these effects are much more pronounced in some systems than in others. Since almost all systems outside a laboratory are usually subjected to temperature changes during their use, it is advisable to know during the design stages how sensitive the proposed system will be to such changes. This is equally important in the systems used to take the original photographs as it is in the systems employed to view these photographs. (The more so in the viewer systems since the heat source in the form of a lamp is built into this equipment).

The image deteriorating effects are many; to name a few:

(1) Elements change shape and the distances between them change with temperature.

(2) Refractive indices of the elements are a function of temperature.

(3) Glass becomes birefringent when heated non-uniformly. Furthermore, pressures on the glass due to the mounting will result in birefringency.

 25X1

These effects will be very difficult to fully analyze. However, it does seem possible to relate the magnitude of the effects with some of the basic parameters of the system, such as the power distribution between the elements, and the magnifications for each element. The purpose of this investigation is again twofold:

(1) Formulate a theory by which the performance of different systems can be classified.

(2) Collect all existing and new data on which to base the study.

Some data are available on existing lens systems, and presently this information is being collected and reviewed for its applicability. However, analysis of results on actual systems can be made in case presently available data proves to be insufficient.

[redacted] 25X1

SECTION C

[redacted] 25X1

IMAGE ANALYSIS RESEARCH PROGRAM

TECHNICAL AND FISCAL PROPOSAL

[redacted] 25X1

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SECTION C

[redacted] 25X1

I. GENERAL DISCUSSION

As time passes, it becomes apparent that present research in the image analysis area is leading to an analytical impasse. The generalized analysis of imaging systems leads to a nonlinear result. Furthermore, the likelihood that film behavior is representable by a linear model daily becomes more remote. Even if one could substantiate the general use of the effective exposure concept, he is constrained to agree that the effective exposure regime is not accessible to the observer, and while such a representation could have merit in system evaluation, it has little applicability to the problem of image exploitation. Present efforts under this program are largely based on the development of suitable models, adequate analyses and definitions in terms of the physical processes. There is a need for concentrated study of a pragmatic nature, wherein one accepts the micro or macro-scopic behavior of films or optical systems and attempts to formulate these results analytically. Thus, the production of an equation representing the imaging process in a transilluminated partially coherent situation may be regarded as the starting point of another problem: how to describe the result in terms which are analytically useful and which offer the possibility of development of intuitive guidelines or handbook type of quality criteria. The same problem applies to film as a representation of some deterministic or stochastic input process. Prediction of results is insufficient. One must be capable of assessing the worth of a system on objective and meaningful bases, even if these bases vary greatly from the usual linear type of analytical or experimental analysis.

[redacted] proposes to enter this region of the problem and to accept 25X1
from both [redacted] information re- 25X1
garding their formulation of imaging and photographic problems. [redacted] 25X1
will therefore provide to the image analysis team the necessary terminal ingredient

in the formulation of analytical techniques for the evaluation of specified nonlinear processes. It is planned that this work will be undertaken gradually, beginning with a relatively minor effort in the next nine months and becoming the major effort in the following period. The primary activity of [redacted] is planned in the areas of: 25X1

1. Nonlinear research
2. Mensuration
3. Laboratory investigation

The mensuration activity will be carried on during the next next nine months with a minor amount of laboratory and analytical work in the following year. Laboratory work in the area of film properties and in support of analytical developments will be carried on continuously throughout the program.

The following information is contained herein:

1. Program for the next following nine-month period, with additional optional activity to allow for the contingency of an expanded program.
2. Program (general) for four subsequent years.
3. Budgetary estimates.

Since we expect the nonlinear analysis study to occupy a major portion of our time, some additional detail in reference thereto is included in a following section of this document.

II. ANALYSIS OF NONLINEAR SYSTEMS - PROBLEM DEFINITION

The concept of modulation transfer function (MTF) as applied to photographic emulsions may be critized on several counts. If the MTF is measured by small signal response at some bias level it represents, at best, the transfer to be obtained at that bias level for small signals. The large signal MTF does not have even that significance. Furthermore, there is a growing body of evidence which indicates that the combination of MTF with effective exposure to compute density distribution for any signal form other than the original test signal (usually a sinusoid) is an invalid procedure. The implication is that linear superposition of frequencies is not a valid hypothesis in the photographic case. This evidence is supported theoretically by the consideration that the number of elements in a photographic record is finite (or at least denumerable) and contains a degeneracy with respect to the exposed scene owing to masking effects among grains. This masking effect, although difficult to formulate rigorously, has some rather easily extracted properties. The most obvious property of a degenerate transformation is that the input is not single valued in the output even in the absence of added noise. That is, even if the location of active sites in the emulsion were a priori known and there were no other sources of image degradation, complete knowledge of developed sites would not yield a complete description of the input signal but would only reduce it to a class of function. Since there is no predisposing reason to assume that one function is preferable to any other we are faced with a situation where we may find "noise" in the absence of noise. Furthermore, the "noise" spectrum will depend in this case on the precise nature of the input function (exposure). As a consequence of this intimate relationship between the signal and the noise (if that term is admissible) statistical treatment and in particular the class of linear statistical analyses exemplified by Fourier analysis are not capable of providing a complete, or in many cases, even an adequate description of the photographic system.

Furthermore, it has been shown[1, 2] that the process of optical imaging is a qualitatively nonlinear process in most physically meaningful cases and is significantly so in most cases connected with the process of image exploitation. The transilluminated case has been explored in depth by Parrent[3] and the results have been verified to a considerable degree by experiment. In cases such as these, the system response becomes specific, i.e., is dependent on the input process, and ordinary analytical methods fail to produce generally useful results.

---

[1] Principles of Optics, Born and Wolf, Pergamon Press

[2] Theory of Partial Coherence, Beran and Parrent, Prentice-Hall

[3] Unpublished Notes, 1966

In 1958 a small book by Norbert Wiener, Non-Linear Problems in Random Theory[4] was published. In this publication Dr. Wiener developed a framework for treatment of nonlinear electrical networks. Since that data there have been about fifty (50) publications, including a number of doctoral theses in electrical engineering, expanding, explaining, applying and modifying that formulation. During the same period alternative formulations have been proposed which offer computational advantages for certain classes of problems. [redacted] has undertaken a small scale study of this literature in an effort to determine the suitability of these mathematical formulations to the problems of imaging system analysis.

Although this study is by no means complete it is fairly clear already that the formalisms currently available are suitable for the treatment of nonlinear electronic systems and that the description in terms of nonlinear functionals is more precise than the linear transfer functions in current use.

What is not clear at this time is the extent of additional computation required for a given improvement in representation. Furthermore, the mathematics are in a state reminiscent of Fourier analysis in the nineteen thirties. That is to say that the formalisms exist but practical criteria for their use are nowhere in sight. There exists also the problem of adaptation of the theory of nonlinear systems to the photographic case. To state dogmatically that such adaptation is clearly possible would be foolish. On the other hand, no clear obstacles to adaptation are known, and the methods are quite general as to the classes of systems represented.

We therefore propose a program of research as follows:

Phase 1: We will continue our study of the literature so as to establish a thorough competency in and appreciation of the several formalisms at our disposal.

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4 Technology Press of Massachusetts Institute of Technology

Phase 2: We will study the convergence properties of existing nonlinear analysis schemes for several classes of nonlinearities. We will endeavor, if necessary, to generate orthogonal expansions other than those currently available in order to provide a system transfer function whose computation is readily amenable to digital computer evaluation and which will admit of a reasonable intuitive interpretation.

Phase 3: We will undertake the adaptation of these methods to the case of nonlinear transilluminated observation, with emphasis on the development of generally applicable descriptive mechanisms and evaluation criteria.

Phase 4: We will undertake to adapt the general methods of expansion in integral functionals to the photographic case. This study will involve consideration of the nature of the photographic process, the extent and degree of nonlinearity to be treated, the nature of the emulsion noise spectrum, and experimental methods for extracting the appropriate data.

Phase 5: We will endeavor to establish an informational base defining sampling criteria and an entropic description of image information content. This will include the treatment of noise in the object space.

Phase 6: Finally, (assuming success in the earlier phases of the work), we will attempt to define a set of tests indicating the most efficient expansion method for a given system and a compilation of computational schemes for determining the transfer function and channel capacity in terms of testing signals appropriate to the type transfer function expansion chosen.

These items are included in the overall program and are referred to as the Phase numbers shown.

TECHNICAL PROGRAM

The proposed program is divided into four task areas. These are: (1) Theoretical study of representation of nonlinear systems, (2) Generation and analysis of controlled sample material, (3) Mensuration techniques to minimize error on small scale objects, and (4) Support as required by [redacted] 25X1

~~1. This item will consist of work preliminary to the primary investigation in the nonlinear representation area (Phase I task). The task will consist of two parts:~~

a) A literature search to evaluate the available material on the subject, and determine the approaches with the greatest potential for usefulness in the photographic case.

b) Selection and expansion of techniques applicable to the general case of partially coherent transilluminating viewing. This case is selected since a considerable amount of theoretical and experimental work will exist as of the time the investigation starts. The success of this phase of Task 1 cannot be predicted until the problem has been given much more detailed study. Possibly rather simple nonlinear methods will suffice to give results that are an adequate approximation for all practical cases of interest. On the other hand, the response of film may be a function of so many variables that considerably more effort is required to generate a model that is satisfactory. This task is therefore delayed until a later phase of the overall program to permit the inclusion of contributing research now planned.

~~2. Generation and Analysis of Controlled Samples~~

This task is essentially a continuation of the effective exposure evaluation. With the experimental setup, carefully controlled functions in exposure can be imaged on film. The present effort has been devoted to only the study of film response to sine waves of a specified spatial frequency. It is also possible to generate functions which are more complicated than this by proper spatial filtering. Since the present program is being used to develop a model of film properties to sine wave stimuli,

[redacted] 25X1

the model can be tested for more complicated functions by comparing the response predicted, versus the experimental results. This effort will thus be useful for experimental material to use in the verification of the theoretical model. One of the primary lines of investigation will include the use of additive stimuli.

3. Mensuration Techniques

This phase will be devoted to two (2) activities:

a) Monitoring activity and support to the SPPF measurement program. Data will be reduced and methods developed as required for the effective continuation of that activity. The objectives are:

   1) Determine the degree of assistance involved in the use of a density related measurement in the mensuration task.

   2) Evaluate quantitatively the error propagation in positive transparency production, from the standpoint of small scale observations.

b) Extension of the mensuration activity by experimental investigation. One purpose is to determine the nature of images in respect to measurement by providing experimental determination of edge properties as a function of local density level and difference in density across the edge. A by-product of this investigation will be guidelines for best use of microdensitometry as a measurement aid. Similar measurement will be accomplished under varying conditions of illumination to determine if repeatability is a function of illumination. Spectrum and degree of coherence will be varied, with a limited number of cases used for each condition.

4. General Support

Support will be provided for other areas of the program, as required by [redacted] 25X1

5. Technical Management and Planning

A certain number of hours must be devoted to technical management and planning. This will include technical coordination, technical reviews, and compliance with major reporting requirements.

1968

1. Continue nonlinear analytical studies, coordinated with [redacted] work in representation of film and imaging systems. At this phase, the extension of the previous work and inclusion of film properties will begin. (Phases II and III) 25X1 25X1

2. Continue and finish laboratory experimentation on mensuration work. Publish final results.

3. Continue laboratory investigation of film properties. Extend methods to synthesis. Define regions in which ordinary analytical methods may be applied, particularly with respect to dynamic range. Conduct other laboratory investigations in support of and as part of (1) and (2) as required.

1969

1. Conduct further investigation into nonlinear system analysis and evaluation. This work should extend well into both film properties and imaging systems. (Phases III and IV)

2. Conduct experimental work in connection with (1).

1970

1. Continue and finalize nonlinear analysis work. Produce analytical and other guidelines for the assessment of exploitation systems. (Phase V)

2. Conduct experimental investigations as required.

1971

1. Finalize results into most tractable form. Produce computational procedures for handling the generalized case in exploitation systems. (Phase VI)

[redacted] 25X1

CHAPTER 3

ADDITIONAL FOLLOW-ON PROGRAMS

SECTION A: IMAGE MOTION COMPENSATION

[redacted] 25X1

INTRODUCTION

[redacted] proposes to perform a program to demonstrate the feasibility of in-line complex spatial filtering for compensating for most types of motion-blurred imagery. The analysis will be directed toward conclusive answers for practical applications of the system. Pending a favorable evaluation of the practical adaptability of the system, it is further proposed that an operational system be designed and constructed. The motivation for this proposed process of image restoration by in-line coherent spatial filtering techniques arose from the development of a computer-driven photofacsimile system. An image restoration filter can be fabricated with the computerized system by direct application techniques employed at [redacted] over several years. The discussions that follow give an outline of the photofacsimile technique and its application to the restoration of smeared imagery. The proposed program is summarized at the end of this section. 25X1

IMAGE RESTORATION

The basic concepts for image restoration rest on the application of frequency domain analysis to optical systems. The advent of complex spatial filtering came with Tsujiuchi[1] who constructed inverse complex filters for coherent in-line filtering. More recently, holography has been applied to complex spatial filtering using the matched filter approach.[2] Some of the applications of coherent spatial filtering at this laboratory have been to compensate for linear motion,[3] defocusing,[4] atmospheric image distortion,[5] as well as pattern recognition,[6] among other applications.

Figure 3-1 is a schematic diagram of a coherent spatial filtering system; it shows the geometry and coordinates used in subsequent analysis. The object transparency to be filtered is placed in the object plane and transilluminated by coherent

25X1

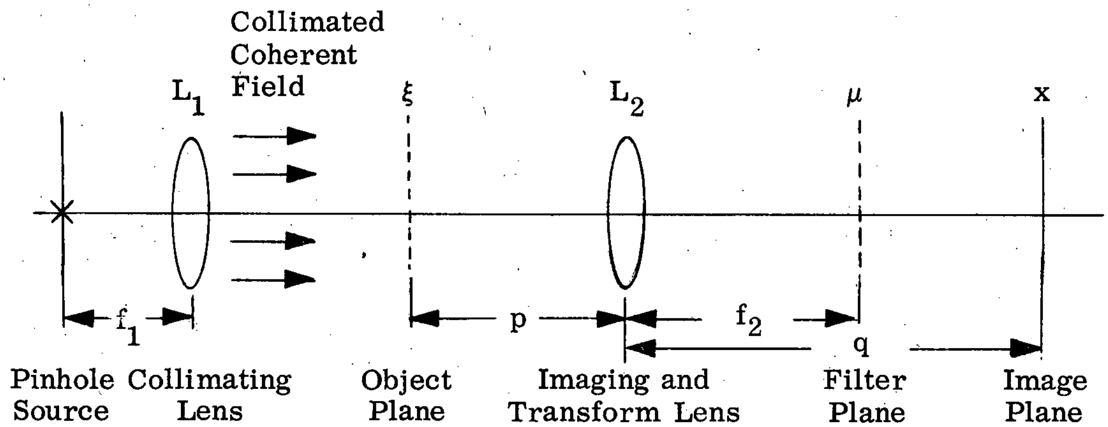


Figure 3-1. Schematic Diagram of Coherent Image Restoration System

collimated quasi-monochromatic illumination. The lens L_2 produces a Fourier transformation of the complex amplitude transmittance $S(\underline{\xi})$ of the transparency. Thus, the amplitude distribution in the filter plane is

$$\tilde{S}\left(\frac{\underline{\mu}}{\lambda f}\right) = \int S(\underline{\xi})\, e^{\frac{i2\pi\underline{\xi}\underline{\mu}}{\lambda f}}\, d\underline{\xi} \ , \tag{3-1}$$

where λ is the coherent wavelength and f is the focal length of lens L_2. For image restoration applications, a filter is placed in the filter plane. In general, a filter $f(\mu)$ has a complex transmittance that can alter both the amplitude and phase of $\tilde{S}(\underline{\mu}/\lambda f)$. Thus, the filtered image distribution $A(\underline{x})$ is given by

$$A(\underline{x}) = \int \tilde{S}\left(\frac{\underline{\mu}}{\lambda f}\right) f(\underline{\mu})\, e^{\frac{i2\pi\underline{\mu}\,\underline{x}}{\lambda f}}\, d\underline{\mu} \ . \tag{3-2}$$

The nature of the filter $f(\mu)$ is, of course, determined by the application. For restoration of aberrated imagery, the input signal to the spatial filtering system is given by

$$S(\underline{\xi}) = O(\underline{\xi}) \circledast \mathcal{S}(\underline{\xi})$$

25X1

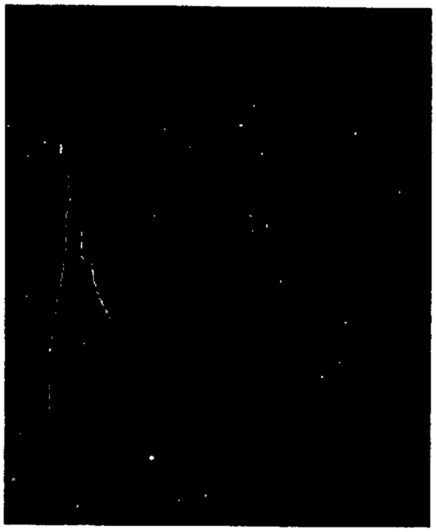
where $\circledast$ denotes a convolution between the object intensity distribution $O(\underline{\xi})$ and the aberrated imaging system impulse response $\mathcal{J}(\underline{\xi})$. The Fourier transform of Eq. (3-3) is

$$\tilde{S}(\underline{\mu}) = \tilde{O}(\underline{\mu})\, \tau(\underline{\mu}) \ , \tag{3-4}$$

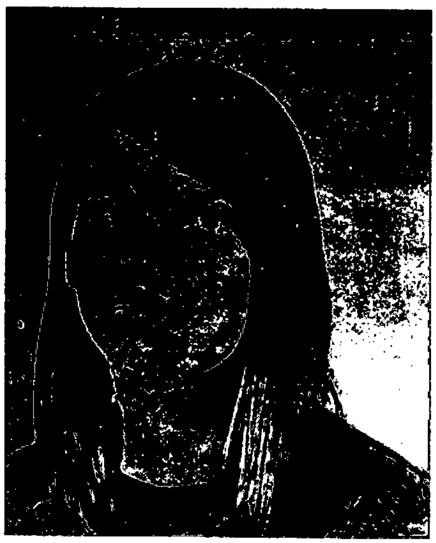
where $\tau(\underline{\mu})$ is the original imaging system transfer function. The transfer function is related by the Fourier transformation to the imaging system impulse response. Any aberrations present in the imaging system response have their transform-related properties in the system transfer function. Thus, one filtering approach to improve the image is to remove the aberrating effects in the transfer function. In this case the appropriate filter is given by

$$f(\underline{\mu}) = \frac{1}{\tau(\underline{\mu})}, \quad \tau(\mu) \neq O \ . \tag{3-5}$$

For linear motion blur, the impulse response can be considered a 'rect' function under conditions where the shutter speed is very fast. Thus, the complex filter constructed for compensation of linear motion blur is a clipped inverse sinc. Results obtained from linear blur restoration have shown a resolution increase by more than a factor of 2, over a dynamic range of 30 dB. Examples of linear motion restoration are shown in Figures 3-2 and 3-3 where, for each figure, (a) is the aberrated image and (b) is the corrected image. Experimental results for correcting five wavelength defocused imagery show a resolution increase of a factor of at least 3.6. The compensating filter was a clipped inverse Besinc function. Figures 3-4 and 3-5 show some results obtained by complex spatial filtering. Inverse filters have been applied successfully to other applications, but were necessarily limited to real functions because it was only possible to fabricate phase plates with 0 or π phase retardations.

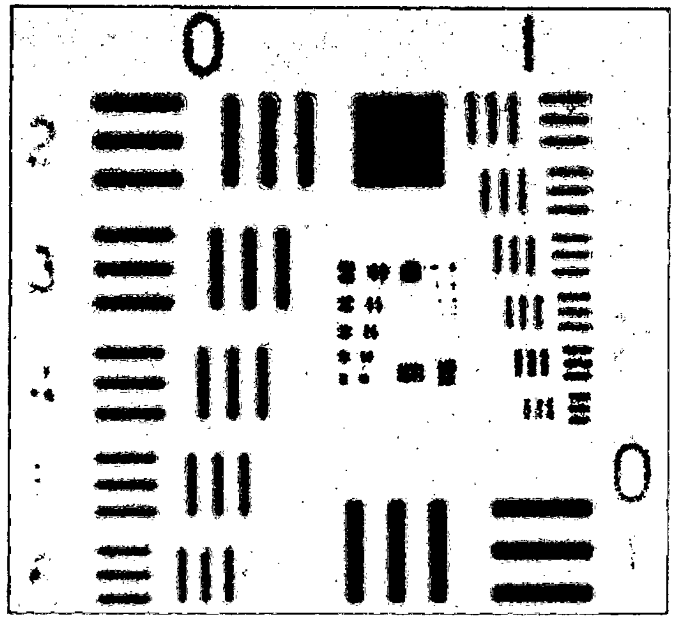


(a)

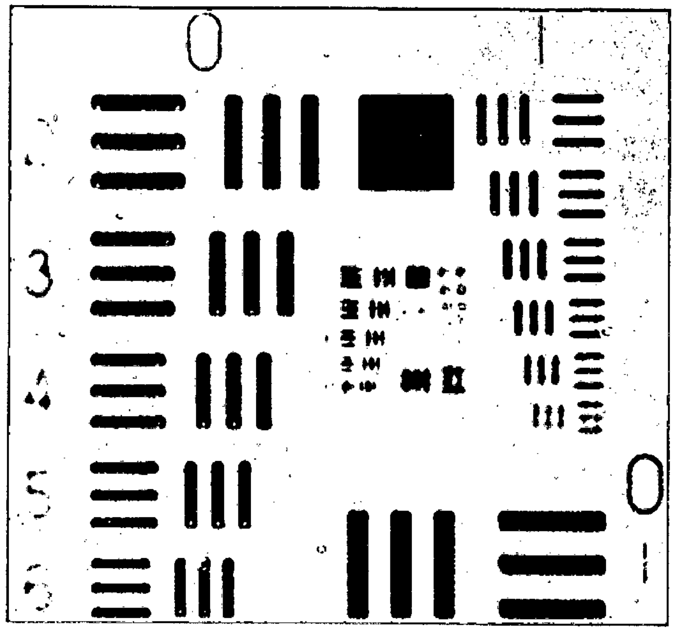


(b)

Figure 3-2. Smeared Image (a) and Its Compensated Image by Inverse Complex Spatial Filtering (b)

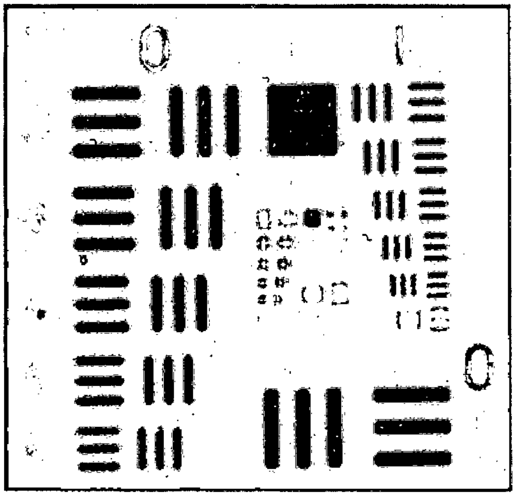


(a)

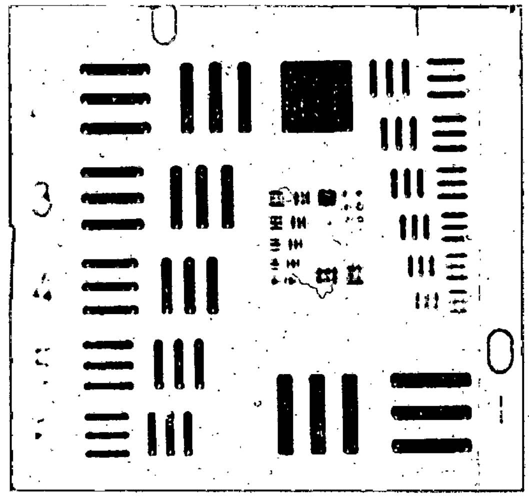


(b)

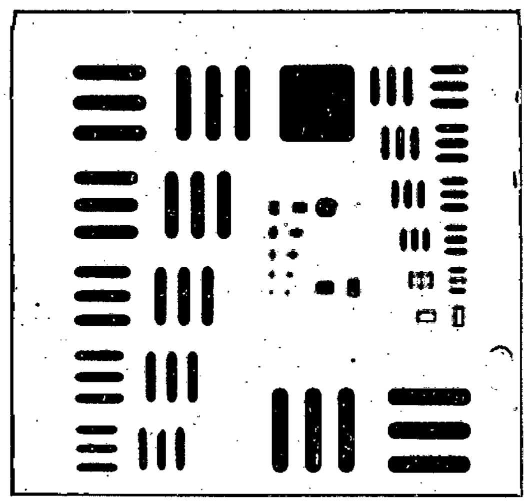
Figure 3-3. Out-of-Focus Image of a Resolution Target (a) and Its Compensated Image by Inverse Complex Spatial Filtering (b)



(a)



(b)

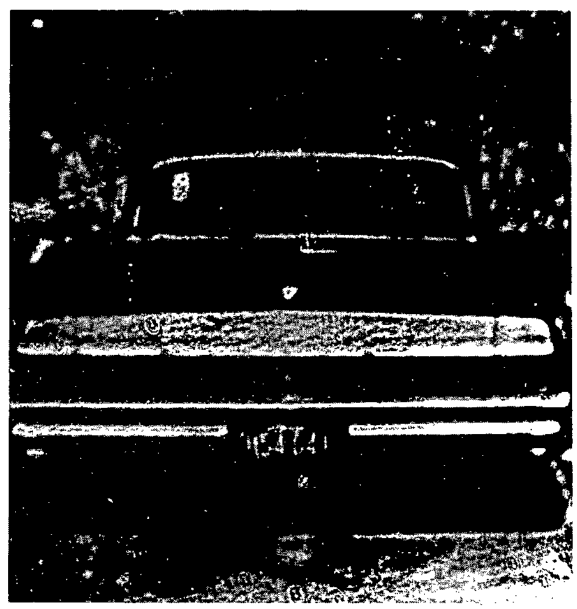


(c)

Figure 3-4. Out-of-Focus Resolution Target (a) and Its Compensated Image Obtained by Inverse Filtering (b) and by Matched Filtering (c)

(a)

(b)



(c)

Figure 3-5. Image Restoration of a 5-Wavelength Out-of-Focus Continuous-Tone Target Showing the Defocused Image (a), and Images Restored by the Two-Lens (b) and One-Lens (c) Filtering Systems

DIGITAL PHOTOFACSIMILE PROCESS

The more general class of asymmetric functions have Fourier transform phase functions that are not limited to two-step functions. To perform filtering operations on such functions, it is necessary to have the capability of recording all phase and amplitude variations. One method by which this is now possible utilizes a digital computer to perform the Fourier transformation of object or impulse information obtained from an optical scanning system response. The phase and amplitude information of the transform are recorded and printed out by a photofacsimile system in the form of an inverse filter. The inverse filter is then used in an optical spatial filtering system for image restoration applications. There are three principal steps in the process:

1. A scanning microdensitometer (ISODENSITRACER®, hereafter referred to as IDT) that, with an analogue to digital converter, provides the input to the computer
2. The Fourier transform program of the computer
3. The photofacsimile process that records the Fourier transform information.

A block diagram of the digital process is shown in Figure 3-6.

The basic capability of the photofacsimile system to print quasi-continuous functions calculated by the computer has been demonstrated. The IDT scanning system for detecting photometric information and recording this information in digital form for computer use has been previously used for edge trace analysis. Thus, the basic capabilities have been demonstrated and it is now necessary to apply this process to image restoration problems of interest. One important problem is the general case of image motion where the motion function blurred impulse response can be asymmetric. An example of an asymmetric motion function and its effective image response is shown in Figure 3-7. This photograph was obtained by taking a time exposure of a resolution target while the camera was moved in an unpredictable fashion. The motion function was recorded separately by placing a pinhole at the center of the target.

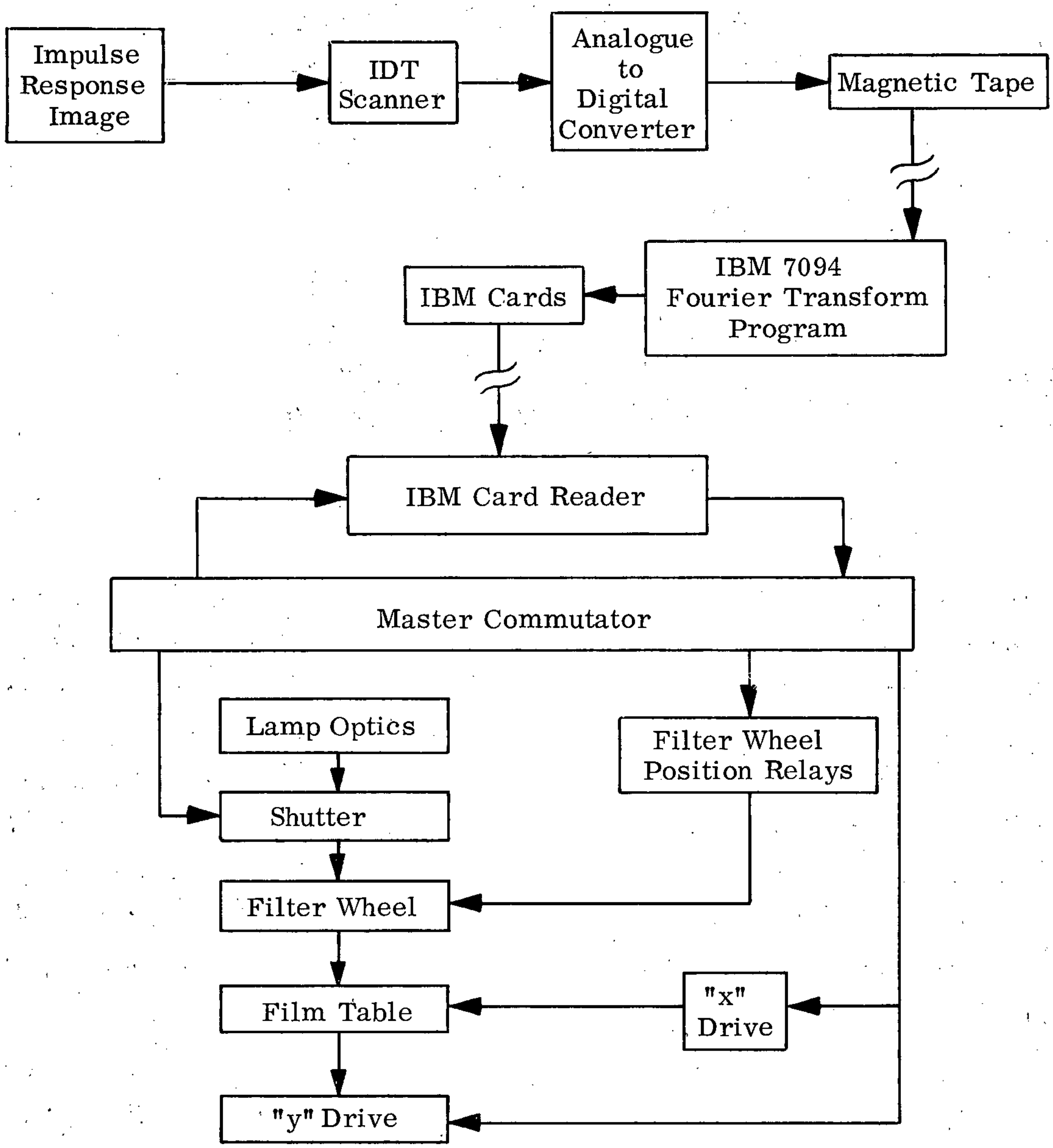


Figure 3-6. Block Diagram of the Digital Solution Using a Computer Program and Photofacsimile Output

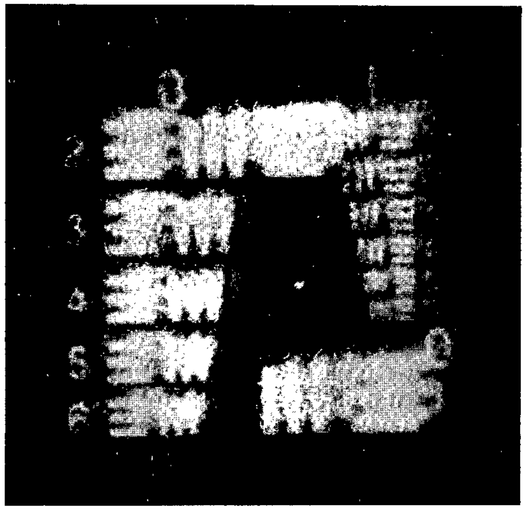


Figure 3-7. Randomly Smeared Image of a Resolution Target

As previously mentioned, a study to compensate for linear motion blur was performed at [redacted] Because linear motion was only one of many possible situations, other motion functions were also analyzed (Table 3-1 and Figure 3-8) to determine the relative merits of the linear motion compensation filter for correcting other types of blurred imagery. The linear motion compensation filter can remove the dc component of more complicated motion functions. With the development of the digital photofacsimile process, it is now feasible that the correct filter can be fabricated for most motion functions. The purpose of the program proposed is first to demonstrate this capability and second to design and construct a system for practical implementation of the principles. 25X1

To provide for a meaningful program, the problem must be limited to one of image blur, and thus exclude other aberrations such as defocusing. Thus we will consider only motion functions limited to a plane orthogonal to the imaging axis. It is further necessary to study the problem from a viewpoint of practical adaptability, and thus the program is divided into two phases. The first phase will determine the practicality of this proposed system and the second phase will provide engineering services necessary for implementation.

TABLE 3-1

SOME MOTION FUNCTIONS THAT OCCUR IN IMAGING

Type of Motion	Velocity Function: Time Coordinate v(t)	Velocity Function: Space Coordinate v(x)	Motion Function M(x)	Symbol Designation
Constant velocity	v_o	v_o	$1/v_o$	M_o
Constant acceleration	at	$(2\ ax)^{1/2}$	$Ax^{-1/2}$	M_1
Constantly changing acceleration	bt^2	$3^{1/3}b^{2/3}x^{2/3}$	$Bx^{-2/3}$	M_2
Oscillatory	$C_{sin}\omega t$	$\omega D\left(1-\frac{x^2}{D^2}\right)^{1/2}$	$\frac{1}{\omega D}\left(1-\frac{x^2}{D^2}\right)^{-1/2}$	M_{osc}
Constant velocity and constant acceleration	$v_o + at$	$v_o\left(1+\frac{2ax}{v_o^2}\right)^{1/2}$	$\frac{1}{v_o}\left(1+\frac{2ax}{v_o^2}\right)^{-1/2}$	$M_o + M_1$

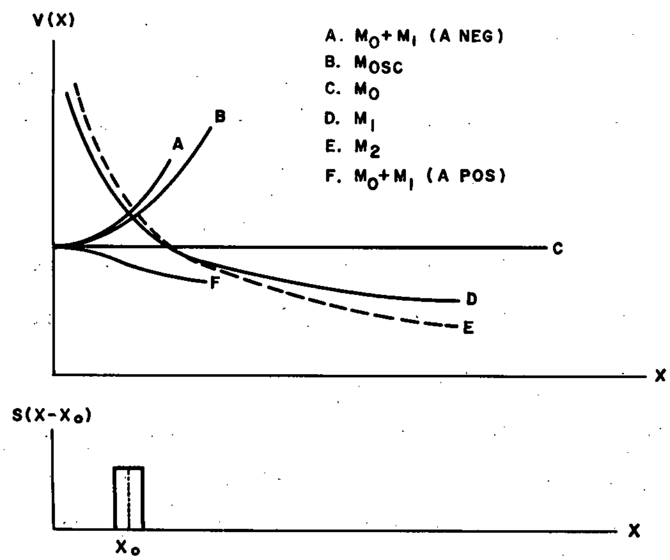


Figure 3-8. Plot of Some Motion Functions of Interest

PROPOSED PROGRAM

Theoretical and Experimental Study

[redacted] proposes to perform a theoretical and experimental study to demonstrate the feasibility of compensating for nonsymmetric motion blur functions using a computer-photofacsimile system to fabricate the necessary inverse filters. Specifically it is proposed that a study be conducted to demonstrate the feasibility of applying the digital computer-photofacsimile system to fabricating inverse filters for spatial filtering of motion-blurred imagery. To perform this study, the response of one component in the digital process must be improved. The IDT scanning technique and tape recording of photometric data of the motion function for computer input requires leasing a tape recorder-readout system. The leased item is necessary so that information scanned by the IDT can be recorded in a form that is compatible with the Fourier transform programmed IBM 7094 computer. At least 10^4 data points are obtained in the IDT scanning process as required information for computer input. By the nature of the Fourier transform program, each point of the computer output is determined from a contribution of every input point. Thus, readout and indexing facility in a tape recorder is imperative. 25X1

Once we have the capability described above, the feasibility of fabricating the required inverse compensating filter can be determined. This feasibility can best be demonstrated by commencing with more simple asymmetric motion functions (e.g. "L"-shaped) and binary targets. The inverse complex filters fabricated from the computed Fourier transform information and the photofacsimile printout will be used in a coherent spatial filtering system to compensate for asymmetric motion blur in imagery. Analysis of the parameters used for computer input and the resulting compensating filter will be made to obtain specific information of the process.

The processes described above will be extended to more complicated motion functions and to continuous-tone imagery. This application is not only the substance of the development, but also the practical goal of the system. Complicated motion functions will be derived by photographing scenes with a time exposure, during which the camera will be moved in an unpredictable fashion. The required filters will be fabricated by the method previously described and spatially filtered images will be presented and analyzed.

Engineering Study

~~An engineering study will be performed for the design concept of an operational system based on specifications determined in the theoretical and experimental study.~~ The determination of a design concept based upon actual experimental results is required to properly evaluate the practical ramifications of the system.

The newly-installed Engineering Research Department of the Physical Sciences Division of [redacted] is actively engaged in the production of custom equipment for the photo-optical field. Engineering and production staff personnel, as well as manufacturing facilities, are available for production of such equipment. The following lists some typical photo-optical instruments that can be manufactured to meet specific customer specifications: 25X1

- Film processors
- Film transports
- Hologram camera systems
- Rear projection film viewers
- Film readers
- Image plane digitizers
- Film scanners.

The Engineering Research Department provides the necessary engineering capability to evolve sound prototype and follow-on equipment intended to demonstrate the concepts developed within the scientific groups. All designs are directed at a high level of performance and reliability consistent with customer requirements within the funds available. Human engineering is heavily considered in all designs to facilitate operation. This arrangement is considered to be of special advantage in areas of classified programs since the research, evaluation, and resultant equipments can be totally developed within the [redacted] facility. The manufacturing facilities include sufficient machine tools and qualified operators to fabricate nearly 100% of any prototype hardware requirements. 25X1

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SECTION E

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VIEWERS

There is a relatively small amount of literature on the subject of viewers. We feel that this field should be investigated thoroughly, and that this study should result in a much better method of writing specifications for future instruments.

Some of the areas to be investigated are:

(a) The field-of-view of a viewer and its magnification are related. Although in general a large field-of-view is desired, it is not known how the increase of field relates to better interpretation by the PI. On the other hand, the aberration correction becomes more and more difficult the larger the field. The trade-off, therefore, cannot intelligently be made.

(b) The objects viewed through the instrument are always films, and therefore display grain. This can be described as "noise." In many other areas a great deal of effort has gone into eliminating this noise. In present day viewers no effort is made to suppress the noise. As a matter of fact, it is not known what magnifications yield the best results.

This subject warrants careful investigation, since the receiver in this case is the human eye, which in itself is a very complicated instrument. Some of the most obvious techniques, therefore, do not work.

(c) The amount of light energy necessary to see the image properly and with the least amount of fatigue to the PI seems to be an unknown quantity. This is, nevertheless, extremely important, since there has to be a balance between the heating of the film material due to high illumination, the comfort of the PI, and the visibility of the image.

Furthermore, the higher the energy requirement, usually the more heat is generated by the light source, and some of this is dissipated into the instrument and its optics. Optical systems, however, form their best images when in absolute temperature equilibrium. The amount of energy to be used in the system should, therefore, again, be properly judged. The factors going into this trade-off, however, are not known.

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(d) Optical devices such as zoom systems, anamorphs, image rotators, etc. are often required. The more optical systems which are needed, the more the image quality reduces. The image deterioration due to these components is not known, nor is it known just where in the optical train these devices should be located. A study should be made to assess these factors.

(e) Alignment of optical systems has a very important effect on the image quality and ease of operation of an instrument. This is especially true of viewers in which the eyepiece-holder can be tilted in different directions.

Tolerances for all optical alignments should be established. Furthermore, procedures should be written to make sure that all misalignments, which arise during the life of the instrument, can be measured and readjusted easily. In many places, in such instruments, designs are possible which make misalignments of components not critical. For instance, when a 45^o prism is replaced by a penta prism, the alignment of the prism becomes non-critical. When alignment among components is critical, it should be known, and the designer should take extra care so as to maintain this alignment.

(f) Stereoscopy is often used. From binocular instruments it is well known that the alignment of the two axes of the instrument becomes extremely important to the proper functioning of the operator. This alignment causes loss of resolving power and gives the operator headaches. In the case of stereoscopic viewers, it is not only the alignment of the instrument but also the alignment of the two film-chips that will determine the quality of the image viewed. Here then is a problem, since the two chips are not identical. Proper ways should be found to align these images. A possible method might be to project two dots onto a properly adjusted instrument so as to guide the eyes to maintain proper direction, and then to align the film strips accordingly.

(g) All the information gathered in the foregoing suggested program should be pulled together into a handbook for the benefit of users of such instruments, since a better understanding will lead to a more efficient use. Also, those individuals who have to write the specifications will benefit from such a handbook, since it will lead to a more precise way of specifying the requirements.

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Special care should be exercised with regard to the language and manner of explanation in such a handbook, so as to make it possible for the users to fully comprehend the information contained therein. The final writing should be done with the help of the customer, so as to be sure that the contents are usable for the customer's purposes.

SINE WAVE RESPONSE OF VIEWING EQUIPMENT, INCLUDING THE OPERATOR

The description of the performance of optical systems in terms of its sine wave response is used more and more frequently. Special equipment to measure the sine wave response of viewing equipment is being completed in [redacted] 25X1 laboratory at the present time.

The sine wave response of the human eye has been measured, and the results have been published in the literature. We would like to point out that the eye is not a linear system, while the theory of sine wave response is based on the assumption that the systems so described are linear. This does not mean that the use of these methods are, a priori, invalid for the eye. It does mean that we should verify the usual assumption that the combination of two instruments, for each of which the sine wave response is known, can be described by the product of the sine wave responses of the subsystems.

Many measurements are made in the field of target recognition. These studies are always done without the use of instrumentation, and no measurement of the eye response of the observer is made. These results are then assumed to be valid when the objects are viewed through optical equipment. Again, these assumptions should be verified.

We therefore propose to measure, in conjunction with your laboratory,* the sine wave response of your equipment, both the equipment alone, the equipment in conjunction with the operator, and the operator alone. The results will then be analyzed, and either the normally-used assumptions mentioned above will be verified or proven to be incorrect.

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SECTION F

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SECTION F

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MICRO SIMULATOR RESEARCH

I. The Requirement: A considerable effort has been directed toward the application of information theory and Fourier transform techniques to the study of micro-imagery. However, as in every information record, the information which can be extracted from the record is a function of the physical characteristics of the reading system. In particular, the appearance of micro-imagery is highly dependent on the illuminator and objective apertures, the coherence and spectral distribution of the light, the field which is illuminated, etc. To relate the quantitative measurements of a microdensitometer or other device to the response of a physically realizable reading system (visual or otherwise), it is necessary to simulate the reading system precisely. Without precise simulation, the measurements of the device cannot be related to the real system.

II. The Solution: Design and fabricate, or modify an existing optical device so that the illumination and objective apertures, the spectral bandwidth, the source focal position and other parameters can be varied independently. It should also be possible to vary the resolution element size as well as the size of the illuminated neighborhood field.

III. The Program: An experimental program should be designed which will demonstrate the ability of the simulator to simulate a variety of optical readout systems. The program should be able to demonstrate quantitatively the effect of the viewing system (i.e., its physical characteristics) on the information content of a recorded image.

IV. An Observation: The "Micro Simulator" approach actually effectively deals with the nonlinearity problem encountered in the partial coherence theory of optical imaging. When the actual system is simulated the nonlinearity which

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occurs has a one to one correspondence to the system under consideration. In this case, the distortion due to the nonlinearity is a directly measured part of the image readout problem and not an unknown perturbation.

EYE RESPONSE RESEARCH

I. Objective: To examine the response of the eye as an optical device, such that observations are free from inference.

II. Background: One of the primary considerations in image analysis is the applicability of straightforward analytical methods. Thus, while the analysis may not produce tractable results, one can at least write down a solution. Such solutions are important only if the response of the eye can be described. If partial coherence produces a non-linear result in the trans-illuminated case and the response of the eye is linear then the result is a closed solution. If the eye does not respond in a linear fashion but produces results highly signal dependent, then one at present cannot assess the meaning of the failure of linear theory in the optical analysis.

III. Specific Objectives: 1. Determine the conditions under which the eye can be treated as a linear optical mechanism. Such experimentation must be performed in a way that precludes inference. The technique must be adaptable to change in the condition of illumination.

2. Determine the applicability of Fechner's law on a small scale. This experiment is difficult to conceive since one is interested in the small aperture case free from surround.

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